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DESIGN OF CONCEPTION ON LIGHTNING MONITORING SYSTEM FOR STRIKES TO STRUCTURES

Проведено аналіз існуючих систем моніторингу блискавок та попередження про грозову активність. Розроблено концепцію системи моніторингу блискавок, які уражують важливі споруди або відбуваються поблизу них. В ній застосовують засоби відеореєстрації, датчики (електричного і магнітного поля, світлового та звукового сигналів) та компоненти для передавання, накопичення і аналізу інформації щодо розрядів блискавок.

Ключові слова: відеореєстрація блискавок, моніторинг блискавок, система моніторингу блискавок, система попереджень про грозу.

1. Introduction

Data on thunderstorm activity are important for various branches and related objects. In particular, this issue is of interest for the electric power industry, aviation and rocket-space branch, industry on mining and processing of fuel and explosives, complexes for processing and transmitting information, forestry, stockbreeding, insurance companies, etc. These data are also used for development of lightning protection normative documents and design of different equipment.

During several decades already, collection of data on thunderstorm characteristics and their development in real time, as well as on lightning parameters, were carried out with the use of automatic systems on remote lightning registration and location (LLS – Lightning Location System), both of terrestrial and satellite basing [1–3]. Such systems are providing information on current thunderstorm activity above large territories. Presently wide prevalence is achieved by detection and direction finding systems (LLS) operating at various countries and regions, and also somewhat simpler systems on lightning activity warning (TWS – Thunderstorm Warning System) covering a certain limited range around the objects. As examples of terrestrial basing systems, one can mention LLS of various manufacturers – VAISALA (LDN, Lightning Detection Network – in North America, in Europe and others), SAFIR, BOLT [1, 2, 4, 5]. Some warning systems are TWS – TLDS, THOR GUARD, LDS Boltek, ATSTORM, LPI LWS [5–9].

LLS in general have large effectiveness on detection of lightning discharges (about 99 %), and their accuracy errors are ranging within about 0.05–4 km. TWS are having somewhat smaller efficiency (20–80 % [10]), and in most cases of their design versions are estimating only approximate distance to lightning (5...40 km) on the basis of electric and magnetic field measurements, and are sending associated warning signals of various potential danger levels to customers. Important point is that neither LLS nor regular TWS provide an exact registration of lightning strike point at the object.

At the same time, according to lightning protection (LP) normative documents that are actual in the world and in

Ukraine (DSTU B B.2.5-38:2008, DSTU EN 62305:2012), one need to carry out a periodical inspection of LP systems at the objects, as well as the objects themselves, in particular at the beginning of the thunderstorm seasons and after each lightning strike. The problem is that, when the object has large dimensions, the execution of such inspections requires significant resources. Also, during exploitation of various objects (like transmission lines, wind turbine generators), it is important to receive not only archive data, but also current information on lightning strikes to objects and possible damages, that will be helpful for effective planning of clearing accident situations caused by lightning activity.

Because of this, versions of TWS, which include video cameras for an accurate registration of lightning strike point at the object, are now actively developed in several countries. In particular, some test lightning monitoring systems (MS) are already introduced in China and Japan, which are based on the use of video cameras [11–14] and allow effectively estimate possible damages in real time (data transmission by 3G network). These systems are still can be considered as a concept approach only, not a full value commercial product, and they require further development. For producing of triggering signal needed to start video capturing, these systems detect light flash from the discharge channel. Specifically mentioned above systems are not combining the video observation and thunderstorm activity warning systems (that is expected for actual TWS), and they do not detect electromagnetic (EM) fields associated to lightning. Sometimes they can miss the detection of lightning, which has no continuous current component, or can have false operation (due to heavy shower, fog, low-intensity light of the lightning discharge channel during the daytime, other optical phenomena, which are not related to lightning). The absence of EM field registration does not provide possibility for getting information on such failures.

For lightning studies in China, a precisely accurate system was designed (China Grid Lightning Detection Network), which combines LLS and TWS, and also includes a high-speed camera having CCD-matrix and other devices [15]. This system allows carrying out the registration of short-time lightning components using good resolution in time

and also performing of reliable calibration for other LLS and TWS. But the price of modern high-speed cameras is large enough – of about 12 000...100000 USD. It is clear, that for lightning MS at various objects one should plan some less expensive technical solutions. In some cases, the research calibration of LLS location accuracy is also carried out with the use of regular video cameras (like in Japan [11]).

Thus, present research is directed to work up some proposals regarding conception of MS for lightning striking to objects, which should have suitable characteristics and features of TWS, include EM-field sensors and regular IP video cameras.

2. The object of research and its technological audit

The object of research considered in this work is the monitoring system for lightning, which strikes specific objects or happening close to them. During this study it is planned to provide proposals on monitoring system based on analysis of lightning characteristics and available technical means. Such MS should be able to detect in time the approaching thunderstorm (at 20–40 km) and also development of dangerous storm situation in situ (for 0.3–1 hour before the first discharge). Also, it should bring to readiness the MS components and provide recording of strike position at the object or in its vicinity, and transmission and saving of related data. An example of existing MS, which have video registration [13], is presented in Fig. 1.

MS can include various sensors (for optical signal, electric and magnetic fields, sound), devices (video cameras, communication means, GPS-receiver for synchronization of records), computer and software means, which all together should provide reliable monitoring of lightning having different types and of accompanying phenomena. The system should register lightning including those having minimal parameters (intensity and duration of current, EM fields, luminosity, thunder). System should record lightning having continuous (portions of seconds or a few seconds) and impulse (tens or hundreds of microseconds) current components, when they present in discharge together or separately.

Also, system should capture both discharges from cloud-to-ground and in reverse direction. Video records ought to have quality good enough to determine the lightning channel and strike point both in daytime and nighttime, including situations of bad weather conditions. System has to operate around-the-clock during whole year. If system is operating in a «sleeping» mode, its triggering into mode of readiness for saving records should occur by using a variety of criteria, which are characteristic for appearance of thunderstorm situation. In case of planning comparison between MS and remote lightning detection networks data, and their common analysis, or of thorough analysis of records from all sensors, one should consider using of accurate GPS-receivers for obtaining time labels and coordinates reference. Thus, video registration of discharge and recording of various characteristics for such short phenomenon like lightning requires special solutions.

When protected structure is the object having relatively small dimensions (tens or hundreds of meters in top view plan), then various MS equipment can be interconnected

and linked to server with the use of electric cables, fiber optic network, and radio communication (e. g., Wi-Fi). If the object is extended at large distances and area (like transmission lines, wind turbine generators plants, pipelines), then connection of separate registration stations and central station can be provided just by radio channels. Such remote registration stations typically have an autonomous power supply.

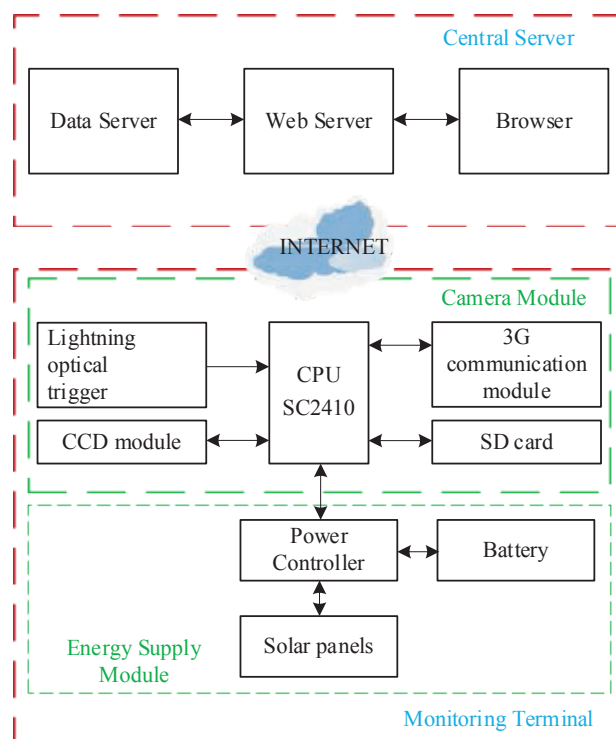


Fig. 1. Diagram of the monitoring system including video registration of lightning [13]

Regarding drawbacks of existing MS having video capturing of strike point, the limited characteristics of cameras can be indicated [13]. In particular, when one using typical regular frame rate of cameras (25...50 fps) and their automatic settings of light sensitivity and exposure, a relatively reliable registration is possible only for discharges with present continuous current component. Also, triggering of saving video fragment with lightning into memory and transmission it to server is usually provided by optical sensor only (Fig. 1). Other sensors are used rarely or their characteristics are not well substantiated. Selection of optical sensor characteristics requires additional analysis and checking. In relatively simple MS, the synchronization of records is typically arranged through the computer networks and has rather limited accuracy (seconds). Such systems are usually operating continuously, waiting for the thunderstorm discharges in the object area and staying in permanent readiness for recording.

3. The aim and objectives of research

The aim of this work is development of conception on monitoring system for lightning striking to large structures and occurring nearby. Its accomplishment will allow laying the basis for a reasonable choice of MS configuration,

modes and algorithms of its operation, and characteristics of its components.

To achieve this goal, the following objectives are planned:

1. To analyze existing storms warning and monitoring systems, to determine their major technical decisions and their shortcomings, and on this basis to propose the conception of a developed system for monitoring lightning that strike large structures and happening close to them.

2. To determine the configuration of the proposed MS, basic modes of its operation, parameters of storm phenomena and lightning that should be detected for triggering of MS and recording.

3. To offer sensors for such system and assess the necessary characteristics of the individual MS components.

4. To perform initial verification of optical sensor performance regarding its registration ability for the short-duration light radiation from the impulse discharge channel having current, which is characteristic for a typical lightning.

4. Research of existing solutions of the problem

The principle of regular warning system operation is based first of all on the analysis of electric and magnetic field variation. During approach of storm front, the intensity of quasi static electric field is increasing, that serves as a signal for triggering TWS and distribution of initial warnings. When changes of magnetic field are detected, that is characteristic for lightning discharges, and when the vector of discharges movement is directed toward the protected object, the system is notifying about approaching storm. To detect magnetic field changes, such systems are using own lightning sensors or additionally make use of information from the LDN [3, 5–9].

Depending on the type of electrostatic field sensors, two main kinds of TWS can be distinguished: with electromechanical fluxmeters and with entirely electronic systems. Electromechanical systems are presented, for example, by products of Boltek Lightning Detection Systems [7] and VAISALA Thunderstorm and Lightning Detection Systems [5] companies. The systems of these two companies, which are additionally analyzed below, are supplemented by lightning sensors, which are able to detect EM-field. Some systems are equipped also by optical sensors (VAISALA). A fully electronic system for electric field intensity measurement is developed and used, for example, by Spanish company Aplicaciones Tecnológicas [8], and it is called ATSTORM.

Canadian corporation BOLTEK produces equipment and software for obtaining operative and analytical information regarding thunderstorm phenomena. The systems of this manufacturer for observation of thunderstorm phenomena in close and long-distance detection radii consist of fluxmeter EFM-100 for atmospheric electric field monitoring and of lightning detectors LD-250, LD-350, and StormTracker [7]. Beside this equipment, a wide variety of auxiliary modules for the information indication, acoustic and light warning, conversion and transmission of data is also available. Main parameters related to electric field registration by fluxmeter EFM-100, according to [7], is included in Table 1.

Finnish company VAISALA produces equipment for industrial measurements [5]. The warning system of this company consists of the following components:

- detector of thunderstorm electric field Vaisala EFM550;

- lightning sensor Vaisala TSS928 including Automated Lightning Alert and Risk Management System Vaisala ALARM;

- thunderstorm warning system Vaisala TWX300 (workstation, interface, software, etc.).

Table 1

Technical parameters of electrostatic fluxmeters

Parameter	Detection radius, km	<i>E</i> -field measurement range, kV/m	Accuracy of <i>E</i> -field measurement, %	Response time, s
BOLTEK EFM-100 [7]	0–38	±20	5	0.1
VAISALA EFM550 [5]	–	±10	5	1
Aplicaciones Tecnológicas ATSTORM [8]	0–20	±32	–	1

The Vaisala Thunderstorm Electric Field Mill EFM550, which main parameters are shown in Table 1, allows measuring of local atmospheric electric field intensity [5]. Its operational principle and design in general are similar to those of fluxmeters from other companies (e. g., Boltec EFM-100).

The Vaisala Thunderstorm Local Lightning Sensor TSS928 [5] is a complex device for monitoring thunderstorm phenomena. It can detect as electromagnetic lightning characteristics (electric and magnetic fields intensities), as well as optical radiation from lightning at close ranges. Manufacturer does not provide all technical characteristics of this device, including that for optical sensor. It is indicated only that optical sensor detects impulse lightning of the sky above the device location. It is supposed that the optical coincident requirement eliminates reporting of non-lightning events. The radius of detecting thunderstorm activity is between 0 to about 56 km. The effectiveness of lightning discharges detection at 19 km in case of one discharge is 90 %, two discharges – 99 %, and three discharges – 99.9 % [5].

The monitoring systems considered above are based on electric field intensity measurements performed with the use of electromechanical «field mills», which made a good showing in warning systems. But they have a significant drawback in their design that is related to presence of movable parts. For this reason, as mentioned, the Aplicaciones Tecnológicas Company have designed and patented [16] a fully electronic device for *E*-field measurements, ATSTORM. Some characteristics of this device are shown in Table 1, according to [8]. Two similar pairs of electrodes 1 and 4 (Fig. 2) are placed at two dissimilar heights (difference *d*), and this allows to have differential measurements of electrostatic field, by measuring related voltage values (V_s). Thus, there is no need to arrange system calibration at the object site when the height of device installation is changed.

The circuit is operating as following (Fig. 2). Due to rearrangement of atmospheric charges during thunderstorm front approaching, electrostatic field induces potentials at measuring electrodes 1. These potentials come to integrating operational amplifiers (OA) 2, where signals are amplified to format convenient for the measurements (V_s). Negative feedback of OA is done through capacitor (not shown). Using of capacitor allows reducing losses and, correspondingly, errors of measured value, when compared to case of using resistor. Such circuit of amplifying input signal is operating

in integrating mode. To avoid distortion of measurement result during signal integration, an inverted input signal V_C is applied to auxiliary compensation electrode 4 with some delay. Such solution allows removing of potential from electrode 1 (similarly to periodical shielding of measurement electrode by rotating grounded electrode in «field mill»), and after some time interval the measurement process is continued.

Several conversions are carried out at the component 3 (e. g., microcontroller). The amplified signal V_S is converted into digital format by analogue-to-digital converter (ADC), then this signal is sent for analysis to interface 5 (for example, to user computer system), where it is interpreted into electric field intensity value. Simultaneously V_S is inverted and sent with some delay to ADC, from which the output signal V_C is sent to electrode 4.

Using of exactly the electronic system for electric field intensity registration allows increasing reliability of the system (no mechanical wear), reducing of power consumption and EM interferences related to electric drive, excluding calibration in cases of changing sensor height position. Electrostatic field sensors of such type can be recommended for the conception of lightning MS.

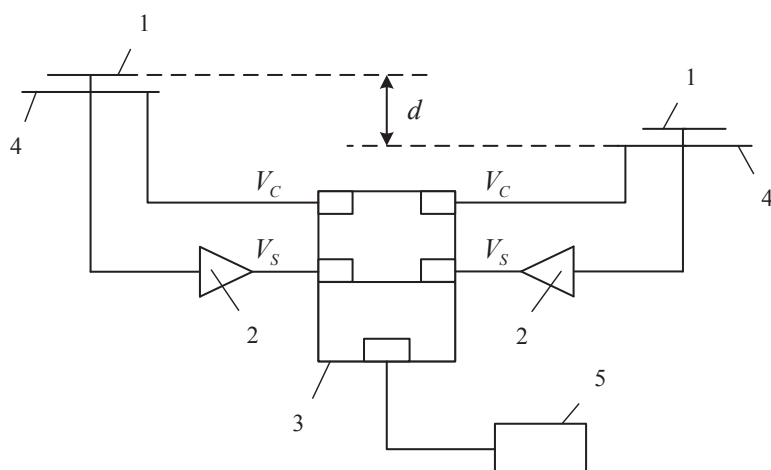


Fig. 2. Scheme of electric field intensity differential measurement device without rotating parts:
1 – first measuring electrode; 2 – operational amplifier; 3 – electronic control device;
4 – auxiliary compensation electrode; 5 – interface [16]

As mentioned, for objects having large dimensions, local lightning monitoring systems are developed in recent years, which contain already video cameras (high-speed and regular) and sensors, including those for triggering recording process [12–14].

Timely and convenient detection of lightning caused damage location is available exactly due to use of video cameras. One of such systems, including video cameras, was designed in China and tested at 500-kV transmission line (Fig. 1) [13]. The operation principle of such system is relatively simple. During lightning flash, the photo sensor is producing triggering signal for saving of a certain frame number into SD-card, and simultaneously this video fragment is sent to the central server by 3G-modem. Power supply can be provided from autonomous module, when there is no possibility to use electric network for this purpose. Autonomous power supply system includes controller for regulation of battery charging process from solar panels. To control the monitoring

system, a single board microcomputer is used, which perform initial processing of information from camera and forwarding it to server. Storage of monitoring system data at server allows accessing it from any place through the Internet network.

Totally there were installed 25 monitoring stations at the 500-kV transmission lines in mounting regions. During 2015, 134 lightning flashes of cloud-to-cloud type and 41 flashes of cloud-to-ground type were recorded. Corresponding samples of still-frames are included in [13]. Obtained records allow determining the points of strikes, estimating damages at the transmission lines and collecting statistical data on lightning discharges at the line route region.

Other systems, which include video cameras, are operating in the same manner [12, 14]. Two main drawbacks of such systems can be mentioned: the possible missing of lightning strike moment by camera and failure to operate of optical triggering system. First drawback is related to situation when video monitoring system can miss lightning discharge and not record it to memory. This can be explained by the fact that the duration of light luminosity from the discharge channel of lightning having only impulse current component can be rather short.

It can be much shorter than the duration of a single frame (20...40 ms) and even than time interval needed for transmission of information from one frame into memory (hundreds of microseconds). Second drawback is related to situation when triggering system is not operating correctly due to various reasons. Optical sensor can be polluted or there is a heavy rain/snow. Or, when storm is occurring during the daytime, there is a bright sky background. For this reasons, when the lightning current is small and, correspondingly, the brightness of channel luminosity is low, the photo sensor can «do not notice» the lightning discharge. Thus, such MS having video cameras need developments, which can include addition of other sensors (electric and magnetic fields, acoustic), refinement of their characteristics and improvement of system operation algorithms.

5. Research methods

For choosing requirements to MS sensors and devices for registration, in this work, data analysis of lightning electromagnetic characteristics based on experimental observations was used. Also, for sensors simulation, the schematic software was applied, analytical calculations were presented, and experimental tests of some sensors for registration system were carried out.

6. Research results

On the basis of analysis of lightning parameters, of existing storm warning and monitoring systems, two variants of lightning monitoring system conception are proposed. Their peculiarity is that they include using of video cameras and other sensors (not only photo sensor). Such solution will allow providing timely determination of location and possibility of estimation damages caused by lightning

discharges to objects having rather large dimensions. In order to record and analyze events for time intervals before, during and immediately after the lightning strike to object, a triggering impulse is used for the MS. It is formed by signals from sensors, which detect such lightning characteristics as electrical and magnetic fields, optical emission, and thunder.

Due to presence of a so-called «dead» time for video camera, i.e. time interval when occurring the reading of information from matrix and saving frame data into memory, sometimes registration may have failure. This time interval can have between tens and a few hundreds of microseconds. In case of only impulse current component in lightning (continuous current is absent in discharge), when its occurrence time coincides with the time interval of reading/saving frame information, the registration of discharge just may not happen. For this reason, signals from other sensors mentioned above also should be recorded into memory, together with the obtained video row. Analysis of records from triggering system sensors will help not only to trigger the monitoring system, but also to estimate whether it was the strike at the object and approximately what parameters of the lightning were. It is worth mentioning that such information will also serve for statistical analysis of the thunderstorm activity characteristics at the object location region.

The control of monitoring system and initial analysis of lightning parameters is carried out by means of a single-board computer (SBC). It saves data to a SD-card and transfers data packages through communication module to server, where storage and detailed processing of obtained information occurs.

6.1. Complex system. The proposed conception on complex lightning monitoring system (MS) is presented in Fig. 3. Its main components are sensor system (SS), video cameras, single board computer, and communication module. The MS having such configuration will allow warning on thunderstorm front approaching to the object, data recording related to lightning strikes, and collection of data on thunderstorms and lightning in the area of object location.

The complex lightning monitoring system operates as following. A «slow» *E*-field antenna is controlled by driver designed according to patent [16], while obtained digital signal is analyzed by SBC. When intensity of *E*-field is increasing to 1–10 kV/m, even in case of no lightning discharges yet, the monitoring system is sending through the communication module to server information on potential possibility or approaching of the thunderstorm.

At the same time, magnetic and «fast» electric field antennas are analyzing the distances to remote lightning discharges. In case of their gradual approaching toward the object (and increasing of EM-field signals' amplitudes), MS is triggered and go out from duty mode, i. e. the cycle video recording into SDRAM starts and simultaneously warning signal is sent regarding danger of thunderstorm appearance.

When lightning discharge occurs in close-range coverage zone of MS (where video observation is taken place), optical sensor and microphone should work, their signals are recorded and serve for producing of triggering signal to save a video fragment with lightning into memory. As cycle video recording is already occurring, then, after action of triggering signal, video fragment having duration of about 1.5 s before and 2 s after the instant of triggering is saved.

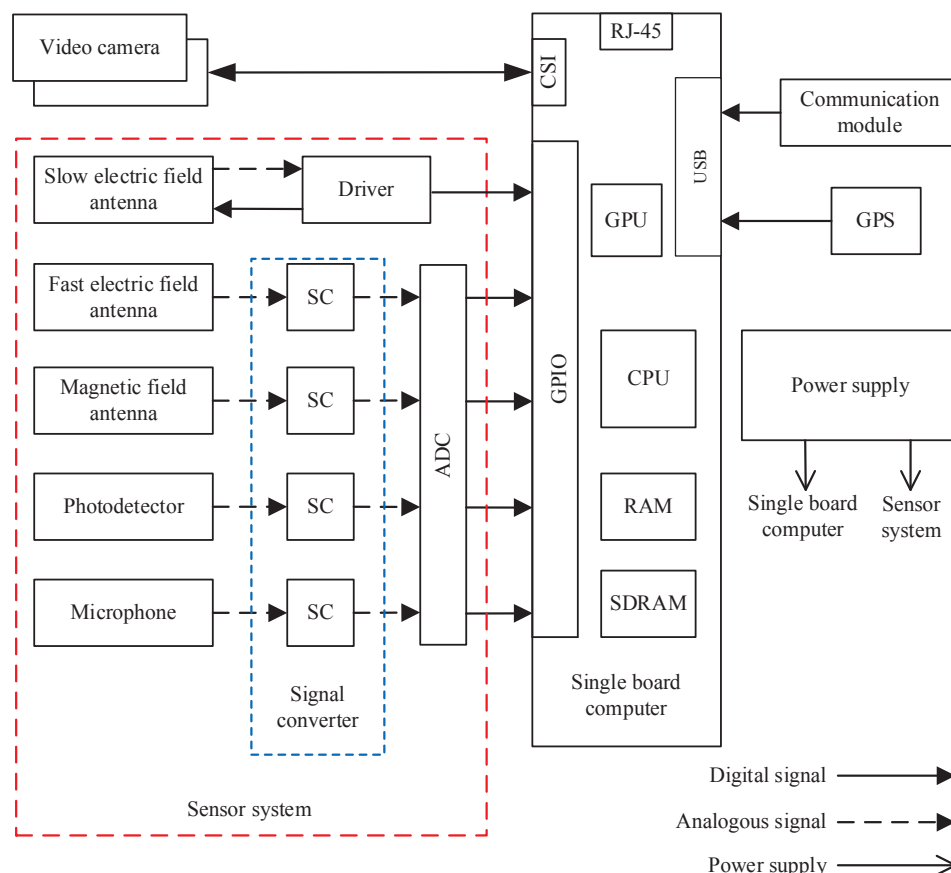


Fig. 3. Diagram of lightning complex monitoring system

These parameters are chosen on the bases of statistical data related to studies of pre-discharge processes and lightning discharges [3, 17–19].

To provide reservation of triggering functions, an analysis of EM field waveforms and amplitudes is used, as the optical and acoustic sensor may sometimes not sense the lightning flash or upward-connected streamers/leaders, which are formed at the monitored object. Some details on levels for characteristics of electric and magnetic field, light and acoustic radiation, to which should react sensors and system, are included further in section 6.3, where different MS components are discussed.

For in depth analysis of information from MS, all parameters registered by SS and which serve as triggering signals, are recorded together with video fragment. Synchronization of records parameters and placing of time labels into records obtained by MS is carried out by using GPS (Global Position System) receivers.

Transmitting of information from MS is carried out with the use of communication module, which can be presented, for example, by 3G modem, radio modules for data transmission, wired lines (twisted pair) or fiber-optical communication lines (FOCL). Using of 3G modem or other radio modules is reasonable when wire or fiber-optic connections to local network are not possible.

Power supply of MS is arranged by connecting to electric network, through the block of voltage transformation and stabilization, by 5 V busses for SBC and communication module, and by +/-20 V for powering SS. As an option, power supply can be provided also by autonomous power unit (including solar panels, battery and charge controller).

Analogous signal from antennas, after amplification and filtration at signal converter (SC), comes to a 4-channel 16-bit ADC, as the SBC typically do not have built-in converter. «Slow» *E*-field antenna does not require conversion of measured value into digital format, as its driver already has built-in ADC.

Information obtained at MS is forwarded to server for further analysis by operator and automatic warning on approaching storm front or strike occurred at the object. As some video fragments, which were obtained after triggering by EM field, may not contain lightning discharge,

for its analysis it is practical to apply computer vision library software (Open CV [20]). Such situation is possible due to changes of EM field background in case of storm front development above the monitored object, when field intensity can exceed minimal parameters set in the system. Using of mentioned library will help to extract only frames containing captured lightning strikes from the video fragments obtained by MS.

It is clear that MS components should have design that provides longtime reliable exploitation in corresponding climate and weather conditions. Also, its electrical part should be protected from over voltages.

6.2. Simplified system. For specific objects, in particular, those extending across large distances and requiring large number of stations, it is practical to consider the version of simplified monitoring system (SMS). To simplify the design of MS and to make it cheaper, the modules of magnetic field antenna, «fast» *E*-field antenna and acoustic sensor can be excluded. Such solution will allow analyzing lesser number of parameters related to phenomena accompanying lightning discharge. For example, the possibility of lightning current amplitude estimation by using magnetic field record will not exist. At the same time SMS will be able to carry out its main function – to warn on approaching storm front and provide monitoring of lightning. Conception of SMS is presented in Fig. 4 and described below.

During storm front approaching, the «slow» *E*-field antenna detects changes of the field, and after increasing of electric field intensity above critical level it triggers the monitoring system and sending a warning signal about approaching storm front toward the object by means of communication module. Triggering of SMS initiates the process of cycle video recording, and video signal in real-time mode is sent to the server.

Server is carrying out processing of video signal by using specialized software, which is based on computer vision library (Open CV). The algorithm of software includes determination of the frame average brightness (it is increased during lightning discharge) and its comparison to that of previous frame. If a rapid change of brightness is detected, then the frames are saved.

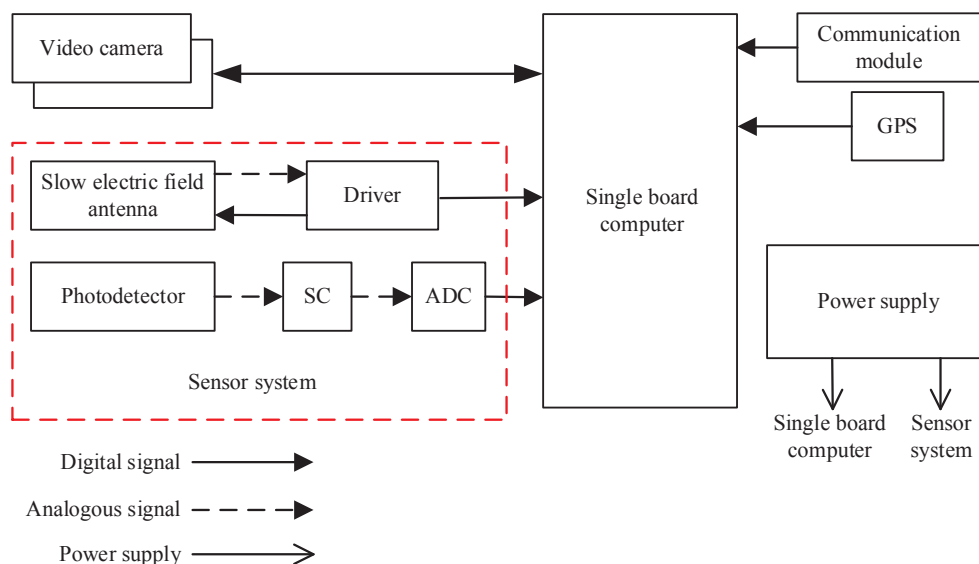


Fig. 4. Diagram of simplified lightning monitoring system

In present SMS, the optical sensor is not used for triggering procedure of saving video record, but only triggers the putting of special time label into video record and allows recording changes of lightning flash intensity in time.

This solution is explained by the reason that the optical sensor can have failure of operation sometimes. It can happen, for example, in presence of bright background (light clouds during daytime) or in conditions of bad visibility (fog, heavy rain or snow). Consequently, if one relies on optical sensor only, the triggering and video capturing may not happen.

At the same time, the analysis by means of software of the whole video row, obtained during action of the storm front, will allow to avoid such situation. Due to existence of the video system «dead» time and possible occurrence of lightning having only short-time impulse component, if corresponding two time intervals will coincide, the video capturing can have failure. The optical sensor will help in this situation, because during following post-analysis it will allow to determine whether discharge had place, how many impulses there were, etc. For this reason, the combination in SS of two types of sensors and video cameras will allow to significantly reduce the probability of missing detection of lightning strike at object by SMS.

Other components of SMS (SBC, communication module, GPS receiver and driver of time labels, power supply) in general have characteristics, which are similar to those in complex MS.

6.3. Characteristics of system components. In this section, the components of MS, reference parameters, for which they should be planned, proposals on possible variants of components' realization, and some other related issues are considered.

6.3.1. Video cameras. The most comprehensive information regarding confirmation the fact and location of lightning strike at the structure is provided by video images. Because of this, discussed MS are based on the use of video cameras. As was mentioned, modern IP cameras considered for MS have the so-called «dead» time, which is related to reading frame information and transferring it into memory. Thus, the matrix does not fix the light coming to its surface during that time. So, in case of short-time lightning (having only impulse component, e. g. return stroke), its registration sometimes may not occur. For special settings of cameras, the probability of such situation is low – not more than 1 %. Of course, this shortcoming can be avoided by using of high-speed camera, but its including into MS is not practical due to large price and because of bulky size of video files, which should be transmitted. For this reason, in MS it is more reasonable to use regular video cameras having special settings of operation mode. The frame frequency can be «regular» – 25 or 50 fps. Preliminary tests, carried out with authors' participation, confirmed the possibility of reliable video registration for discharge channels with impulse currents having duration of a few tens of microseconds.

For MS, it is suitable any IP video camera, that have extended settings. For proposed conception of MS and SMS, for example, one can consider using of a Raspberry Pi Camera Module v2, which parameters are presented in Table 2, according to data in [21].

Table 2

Parameters of Camera Module v2

Image sensor	Sony IMX 219 PQ CMOS in a fixed-focus module
Resolution photo	8 Mp, 3280x2464
Video	1080p: 30 fps, 720p: 60 fps
Control functions and other	Exposure control White balance Band filter Luminance detection 50/60 Hz Black level calibration

6.3.2. «Slow» electric field antenna. This antenna allows measuring of electrostatic field changes near the ground surface. The registration of these changes provides possibility to forecast approaching of the storm front or origination of storm clouds in the zone of object location. The range of measuring E -field intensity changes should be of ± 30 kV, and response time of ~ 1 s.

For developed conception of MS, a solution is accepted not to use the «electric mills» for registration of electrostatic field intensity. This is because of presence movable parts there (and, thus, their limited lifetime) and necessity to carry out calibration for installation them at a certain height. Instead, a variant is accepted on using of fully electronic measuring system, for example, designed according to [16].

Among ready solutions for analysis of electrostatic field changes, one can consider sensor ATSTORM [8] from Aplicaciones Tecnologicas Company, which is using the electronic measuring system in accordance to [16]. The price of the sensor is considerable. Because of this, it could be reasonable to design the analog of such sensor having following characteristics:

- transmission bandwidth is 0.1–10 Hz;
- ranges for electric field measurement is ± 30 kV;
- no need in sensor recalibration in case of changing its installation height.

6.3.3. «Fast» electric field antenna. This antenna allows evaluate dynamic changes of E -field, which occur during discharges of various types (in clouds, between clouds and ground). Again, one can consider the ready devices including such antennas [5]. On the other hand, such devices can be designed at the phase of development of a certain MS. The basic issues for such a design are described below, according to [17].

Physical configuration of the «fast» electric field antenna is including a metallic rod insulated from the ground (whip aerial) or a flat plate, which are connected to the electrical circuit. If dimensions of antenna are much less than the minimal wavelength of measured E -field, then this antenna will serve as a capacitive source of voltage, which will be varied in time and which voltage value will be proportional to the background electric field $e(t)$.

In equivalent circuit of antenna presented in Fig. 5, the following notations are accepted:

$e(t)$ – equivalent source of the background electric field intensity;

h_e – effective height of antenna;

C_a – equivalent capacitance of antenna;

C_c, R_c – equivalent capacitance and resistance of cable, which is used to connect antenna to the circuit;

C – capacitance of the measuring circuit;

R – resistance of the measuring circuit for controlling the decaying time constant.

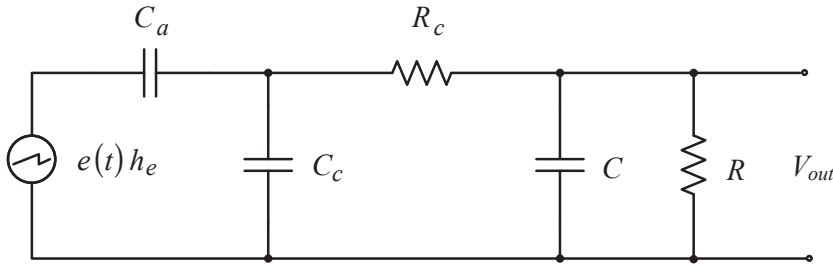


Fig. 5. Equivalent circuit of the *E*-field measuring system using «fast» antenna [17]

Some expressions for selection of parameters in case of rod antenna are following. The effective height of antenna (h_e) can be defined as a relation between voltage of the equivalent open circuit of antenna (V_p) and intensity of electric field in direction of antenna polarization (E) [17]:

$$h_e = \frac{V_p}{E}. \quad (1)$$

For initial calculations, it can be taken $h_e = 1$ m, and then this value can be defined more accurately from experiments and used as a constant. The output signal $v(t)$ in such circuit is [17]:

$$v(t) = E_0 h_e \frac{C_a}{C_a + C_c + C} e^{-(t/\tau_d)}, \quad (2)$$

$$\tau_d = R(C_a + C_c + C), \quad (3)$$

where E_0 is the amplitude of field intensity, which is assumed a step function.

Time constant τ_d determines the lower frequency limit of the bandwidth of the measuring system. The lower frequency limit of the bandwidth (below 3 dB) is determined as $1/(2\pi\tau_d)$. To obtain accurate measurements of the electric field varying in time, the time constant should be much larger than the total duration of the field waveform. As shown in [17], in order to carry out field measurements with the engineering accuracy, if field waveform duration is about 100 μ s, the decay time constant of the measuring system should be of about 1 ms.

The upper limit of the measuring system frequency bandwidth is determined by physical dimensions of antenna, by electronic components used in the system, and by parameters of the system that recording the output signal. If l is the rod length, it is necessary to satisfy condition $l \ll \lambda_m/4$, where λ_m is the minimal wavelength of the measured electric field. In order to carry out the measurements of *E*-field related to lightning strikes, the upper frequency limit of antenna system should be higher than about 5...20 MHz [17].

The relations for the measurements with the use of «fast» *E*-field plate antenna can be considered in the same manner. Also, there were performed simulations of the circuit by using the SPICE-type software Micro-Cap for antenna having plate of the radius $r_p = 120$ mm. For the minimal registration frequency of the «fast» *E*-field of 1 kHz, the condition $2 \cdot r_p \ll \lambda_m/4$ is satisfied. The plate is placed above the grounded housing at the height of $h = 50$ mm.

A coaxial cable (1 m, 50 Ohm, 80 pF) is used to connect antenna and amplifier circuit. Other circuit parameters are following: integration capacitor – 15 pF, discharging resistor – 99 mOhm, time constant – $1.485 \cdot 10^{-3}$ s [17].

In simulation, for the equivalent source $e(t)$, there were used oscillograms and data on the intensity of *E*-field taken from the experimental observations of actual lightning at close (22 m [22]) and remote (1 and 10 km [19, 23]) distances. Data from [22] have allowed determination of the minimal electromagnetic field parameters related to lightning having minimal current amplitudes, which were obtained at the distances of 20 and 22 m from the stricken structure (100 m tower, 44 records of return strokes). Parameters obtained for minimal current amplitude value are shown in Table 3, and these can serve as the threshold values for triggering MS and SMS. The waveforms of *E*-field impulses were approximated by using typical field oscillograms [17, 22, 23] related to various distances from lightning (22 m, 1 and 10 km) and then utilized for setting antenna input signal.

The results of simulation are presented in Fig. 6, where one can see the oscillograms of the input and output signals at the *E*-field registration circuit.

The values of obtained signals at the circuit output, which correspond to peak parameters of the field, are presented in Table 4. These output signals may serve for producing of triggering signal to save video fragment into memory.

In Table 4, the output voltage for the case of distance 22 m is 46.6 V, which is lower than for the case of 1000 m (405.2 V). This is because the data taken for simulation case of 22 m are related to lightning having minimal current ($I = 1.8$ kA), while for cases of distances 1000 and 10000 m there were taken average values of electric field intensities produced by various lightning, according to [23].

The summary of requirements to characteristics of sensor using «fast» *E*-field antenna is following:

- transmission bandwidth is from 1 kHz to 5...20 MHz;
- minimal output voltage from antenna system, which may serve as a triggering signal to save video record, is about 45 V;
- limiting of the output signal amplitude at SC for the ADC.

Table 3

Minimal values of lightning current and related electromagnetic field parameters*

Parameter	I , kA	H , A/m	ΔE_L , kV/m	ΔE_{RS} , kV/m	RE , kV/m	T , μ s
Value	1.8	40.6	0.6	1.5	-0.9	4.6

Note: * – data are taken from [22]; H – magnetic field intensity, ΔE_L – vertical electric field intensity produced by leader, ΔE_{RS} – intensity of *E*-field during return stroke phase, T – time when the electric field intensity associated to leader reaches half of its maximal value, RE – resultant electric field obtained from expression: $RE = \Delta E_L - \Delta E_{RS}$.

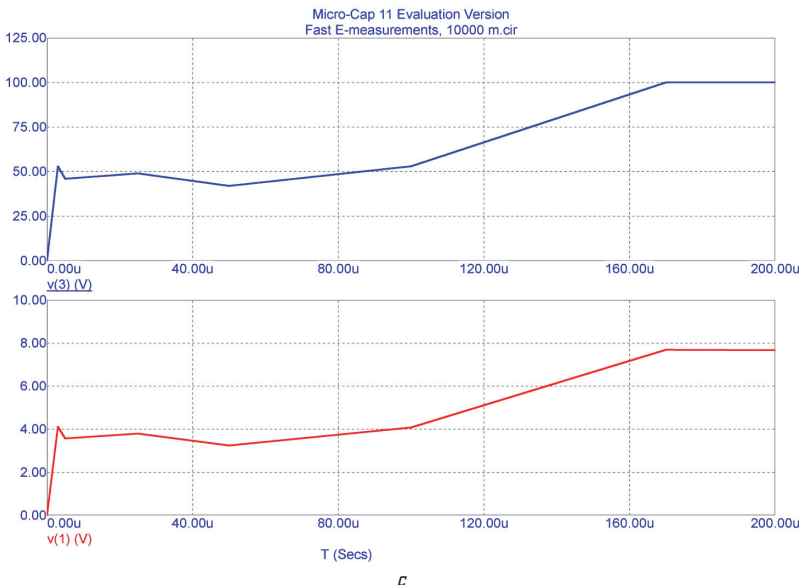
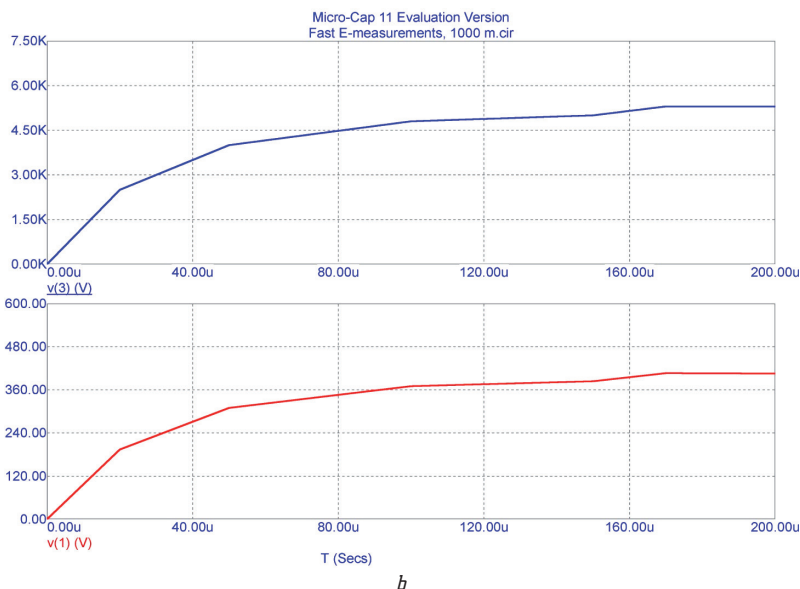
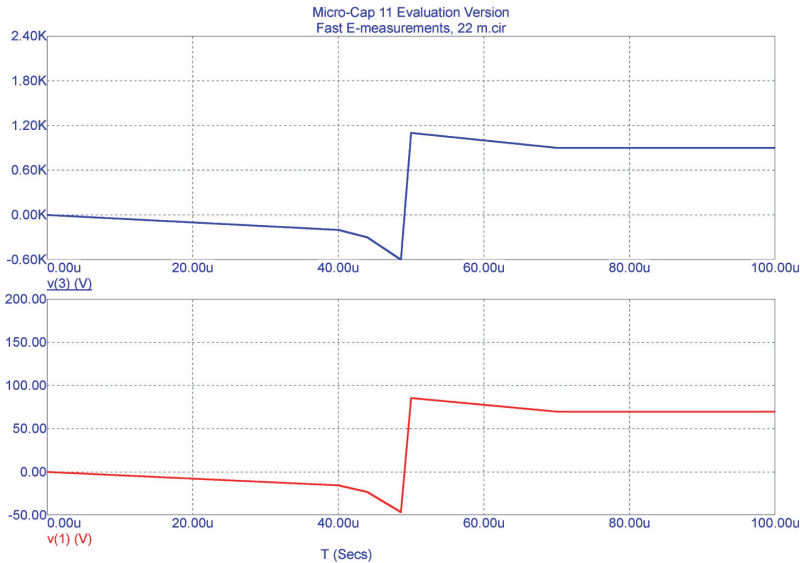


Рис. 6. Variation of the input signal (top curve) and output signal (bottom curve) voltages in time for the plate antenna placed at various distances from lightning: *a* – 22 m; *b* – 1000 m; *c* – 10000 m

Table 4

Peak voltage parameters at the antenna output obtained for lightning distances of 22, 1000 and 10000 m

Distance, m	22	1000	10000
Antenna output voltage <i>v</i> , V	46.6	405.2	7.7

6.3.4. *Magnetic field antenna.* To measure the magnetic field produced by lightning, one can use loop of wire. The voltage induced in this open-circuit loop is proportional to the rate of change of magnetic flux crossing the loop area. Considering that the loop area (*A*) is small, it is possible to assume that the normal component of the magnetic flux density B_n is constant for the whole loop area, and one can write [18]:

$$B_n = B \cos \alpha, \tag{4}$$

where α is the angle between the magnetic flux density vector and vector normal to the plane of the loop. The induced voltage in the loop:

$$V = A \frac{dB_n}{dt}. \tag{5}$$

When $\cos \alpha = 1$ ($\alpha = 0^\circ$), the induced voltage is maximal, while in case of $\cos \alpha = 0$ ($\alpha = 90^\circ$) the induced voltage is zero. From this one can conclude that the value of induced voltage for the vertical loop antenna in given position depends on the direction to the field source, and, consequently, two such antennas, having orthogonal mutual orientation of their planes, may serve for finding direction to the source of magnetic field [18]. Thus, to obtain a full horizontal (azimuthal) component of magnetic field, which is dominant for the lightning having vertical channels, it is possible to use antenna consisting of two vertical loops. As the signal at the loop antenna output is proportional to derivative of the magnetic flux density (5), for obtaining the magnetic flux density it should be integrated. This can be done by using of RC or RL circuits. Also, the measured signal can be integrated numerically. As an example, below is considered the case of using RC-integrator. An equivalent circuit of magnetic measuring system is shown in Fig. 7, where corresponding parameters of antenna, integrator and recorder are notated.

There are three conditions to be satisfied for the undistorted registration of magnetic field by discussed measuring system [18]:

- 1) $R \gg 1/\omega C$ ($\omega \gg 1/(RC)$; C_m is neglected), which define the low frequency limit of the bandwidth, and is equivalent to condition $\Delta t \ll \tau$ ($\tau = RC$); where ω is the equivalent angular frequency of the magnetic field signal;

- 2) $R \gg \omega L$ ($\omega \ll R/L$), which define the upper frequency limit of the bandwidth;
 3) $R_{in} \gg R$, which provides that C is discharged first of all through the R , but not R_{in} .

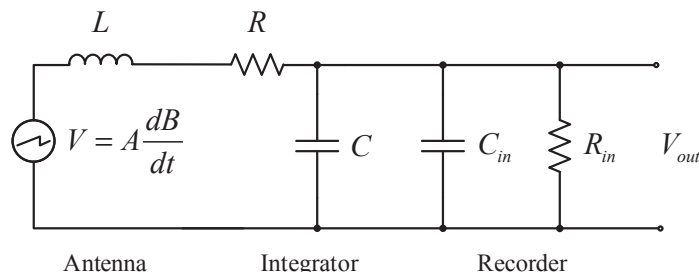


Fig. 7. Equivalent circuit of magnetic field measuring system [18]

When these three conditions are satisfied, the output voltage does not depend on the frequency and determined as following [18]:

$$V_{out} = \frac{A \cdot B}{R \cdot C} \quad (6)$$

In order to provide shielding of magnetic field antenna from the influence of E -field, the loop antenna can be placed within the shield, which is cut in the middle. For this purpose, a coaxial cable is often used as antenna for registration of lightning magnetic field, in which the external shield is grounded and broken in order to avoid appearance of the short-circuit turn [18]. In this solution, the inner conductor of the cable is used as the loop antenna.

Sometimes using of the loop antenna in MS is not convenient, because of its large dimensions (the diagonal of the loop antenna having one turn can be of 1...2 m). The reduction of the antenna dimensions by several times can be achieved in case of using several turns or ferrite rods. But ferrite antenna requires larger number of turns and has a lower resonance frequency, if compared to loop antenna. The resonance frequencies of the ferrite antenna for the wideband detection, which corresponds to the main spectrum of the lightning magnetic field radiation, should be lower, than 30...100 kHz [18, 24].

For the SMS, as a detector of the lightning discharges and indicator of approaching storm front, one can use, for example, a ready sensor MOD-1016 [25]. Regarding its advantages, it can be mentioned the compact design, low power consumption, registration range up to 40 km, and digital interface for connection (SPI, I2C). Among disadvantages, it should be indicated that the waveforms of magnetic field signals are not recorded and that there is no detailed information on lightning parameters corresponding to calibration of the sensor.

The summary of requirements to characteristics of magnetic field antenna:

- transmission bandwidth is from 3 kHz to 30 MHz (or better - 100 MHz);
- providing of antenna compactness (ferrite rod).

6.3.5. *Optical sensor.* Using of optical sensor on the basis of photodiode allows triggering of MS by lightning discharge at or near the object. Distance to lightning, at which optical sensor can detect it reliably, according to data [11, 26], is about tens and hundreds meters, that is quite enough for triggering the system that monitoring strikes to the objects. In contrast to situation with the

optic sensor, the signals from field antennas depend on their location, presence of other large structures nearby, which can change field parameters, and on lightning current characteristics. Powerful lightning at the large distance can create field having the same intensity, as will be produced by lower current at close distance.

As a ready lightning detector product, which contain optical sensor, it can be mentioned the Vaisala Lightning Sensor TSS928 [5]. Among other characteristics, it also detects the optical radiation at close distances, the so-called bright flash in the sky. The manufacturer does not provide detailed characteristics of the optical sensor. Also, in description of already discussed system having video registration, which is used for monitoring of 500 kV transmission lines [13], it is indicated the presence of optical sensor, but there is no detailed information on its characteristics.

Authors have tested the optical sensor of own design, which is using a fast photodiode having maximal sensitivity in visible and infrared range (0.3–1.1 μm). Preliminary tests have indicated that the developed circuit provides registration of the impulses with resolution at the front not worse than 1 μs . Tests of the optical sensor module have been carried out at high-voltage generators of impulse voltages (IVG) and of impulse currents (ICG). For example, tests with the ICG (Fig. 8) provided possibility to obtain impulse arcs having peak currents of 20...30 kA, similar to those in typical actual lightning during the return stroke phase [19]. Time characteristics of the used oscillating impulses (5, 27, 40 μs – time of the 1st, 2nd, and 3rd peaks, correspondingly) are related to the range of minimal values of impulses durations, which are observed for strikes of typical lightning. For example, in cumulative distributions of impulse duration values for the currents of first lightning strokes, the 95-% probability corresponds to duration value of ~30 μs , while for the subsequent strokes it is 6.5 μs [19].

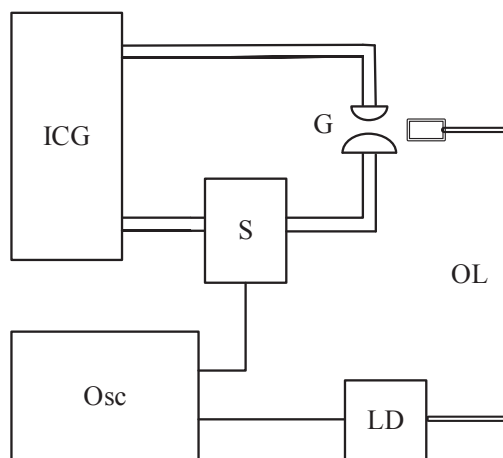


Fig. 8. Experimental setup for tests of optical sensor by impulse current generator (ICG): G – electrodes of the discharge gap; S – shunt; OL – fiber-optic line; LD – optical sensor module (light detector); Osc – oscillograph

The experimental oscillograms of the oscillating decaying impulse current for the discharge in a short gap (5 mm) and corresponding signal from optical sensor are presented in relative units in Fig. 9.

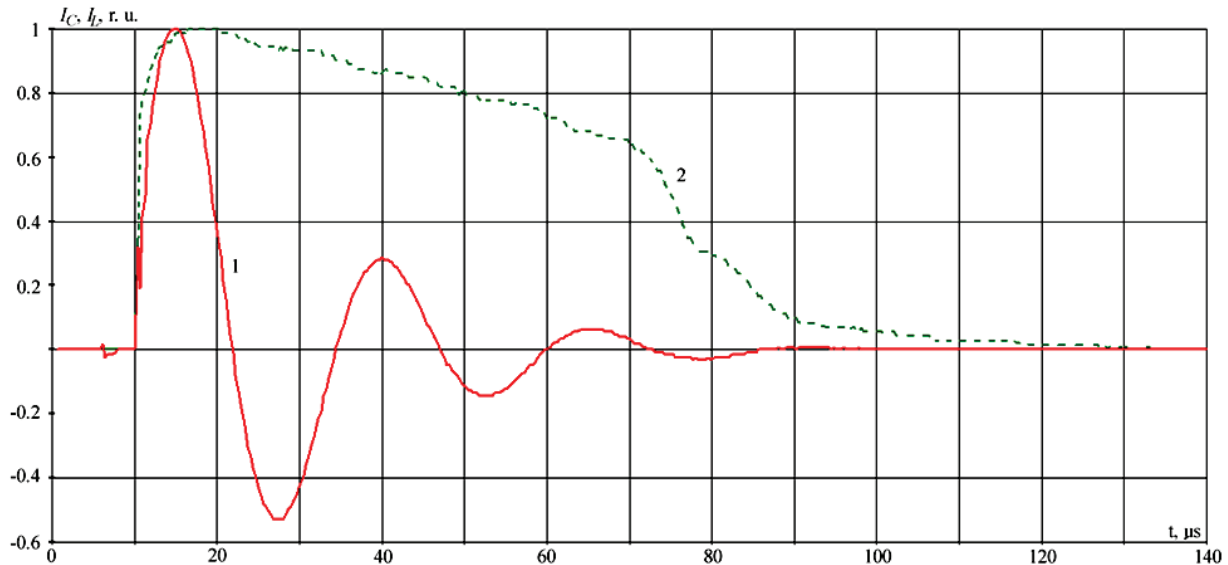


Fig. 9. Oscillograms of current impulse in discharge (I_C , curve 1) and of optical sensor signal (I_L , curve 2) in relative units: current – record from the shunt, 21 kA; time t – in microseconds

The current waveform was recorded by using a resistive shunt having low inductance, and current amplitude for presented test result was 21 kA. The oscillations of current are decaying practically completely during 80 μs , while the intensity of optical signal began to decrease rapidly after 60 μs (time of decrease to half amplitude value is 65 μs). But then the optical signal is decaying much later (120 μs) than the current signal. The peak value of the optical signal is reached with some delay ($\sim 3.6 \mu\text{s}$) when compared to the current peak. In general, test results are in agreement with the observations of other researchers on the delay of light radiation (1.8 μs) and its lag (inertia) in case of natural lightning [27]. The issues of optical radiation power were studied in [27, 28], and, for example, for the discharges having current amplitudes of the strokes 10 and 19.7 kA at the distance of 200 m, there were obtained values of 503 and 2075 W/m^2 , correspondingly [27].

Thus, the summary on requirements to characteristics of optic sensor is following:

- uniform sensitivity in the visible and close infrared range (0.4...1 μm);
- time resolution – 1 μs , distance of lightning registration – up to 500 m;
- parameters of formed triggering signal at the circuit output – 5...10 V, 0.1...0.5 s.

6.3.6. Acoustic sensor. All main types of discharges (in clouds, between clouds, cloud-to-ground and reverse) are able to produce thunder. Studies indicate that main spectrum of the acoustic radiation of remote lightning is in the range of 0...150 Hz and having peak near 100 Hz [29]. Considerable power is also present at the infrasound range (0...20 Hz) [29]. At the close distances, the thunder spectrums were studied with the triggered lightning [29], and the main acoustic spectrum is obtained in the range of approximately 200...1800 Hz. Thus, to register the thunder, one may consider using of the capacitor microphones, in which low-frequency limit of their bandwidth is about 0.5 Hz. The upper limit of their frequency bandwidth may reach tens of kilohertz. So, the acoustic sensor should have a filter, which will limit sound registration to the upper frequency of 1...2 kHz.

7. SWOT analysis of research results

Strengths. The positive results of present research is the proposal on conception of the monitoring system for lightning that strikes the objects, which has an extended possibilities in comparison to existing storm warning and monitoring systems. This is provided due to substantiated choosing of types and characteristics of sensors, which register various characteristics of phenomena that accompanying lightning discharge, and due to using of several video cameras. Realization of such MS hopefully will allow registering with high efficiency of the lightning of different types striking at the object and nearby, and also accurate determination of the strike location. This will provide technical and economical gain during exploitation of the large objects and maintenance of their lightning protection systems. Also, it will provide possibilities for analysis of strikes by lightning and for effective planning of clearing damages, will give statistical data on thunderstorm activity at the region of object location, and information for improvement of protection means. In addition, another positive result is the proposal of two variants of the MS (complex and simplified), which gives some flexibility in selection of MS depending on the characteristics and peculiarities of the protected object, conditions of exploitation, requirements on reliability, economical abilities, etc.

The development of modern high-technology thunderstorm activity MS, in addition to scientific and application findings, will allow solving of several practical tasks for various areas. In particular, this will promote the development of new approaches to design of engineering structures and modern lightning protection systems, to safe exploitation of various objects, to reduction of economical losses related to thunderstorm phenomena, as well to providing safety for people.

Weaknesses. As weak sides of the proposed conception, it can be indicated a certain complexity of the complex MS and presence of the large number of components. Additional studies, development and resources are required for addressing issues on selection of registration modes for regular video cameras to capture the short-time components

of the lightning discharges, on tests of the sensors also in nature conditions, and on development of software for the entire MS.

Opportunities. In further work, it is reasonable to study the possibility of MS structure optimization for different types of objects, of reliable operation during various periods of the day and different weather conditions. Also, it is needed to develop in details the algorithms of corresponding MS variants operation and of software, in order to approach the hundred percent of video registration for lightning events at the object.

Threats. This issue can be related to the need of additional recourses for the development and testing of MS, for its purchasing, installation, maintenance, and for current analysis of the data, which will result in some increase of the products cost at the enterprises, where such MS will be introduced.

8. Conclusions

1. Analysis of existing thunderstorm warning and monitoring systems is carried out. It is found, that in some local systems, the main shortcoming is the absence of video registration means, which does not allow determining the location of strike at the objects. In systems, where such cameras are present, it is necessary to develop more reliable approaches to triggering of recording by the system and further analysis. On the basis of analysis, there were worked out two variants of the monitoring system for lightning striking large structures or happening nearby – the complex MS and simplified MS (SMS). In both systems, video cameras and additional sensors are used.

2. The configurations of proposed MS are determined, and the main modes of their operation are described. Using data on lightning studies, the parameters of thunderstorm phenomena and lightning, which should be detected for triggering of MS and recording, are determined too. It is recommended to use additional sensors (electric and magnetic field, acoustic) for reliable triggering of MS and also several video cameras. In both variants of MS, for extraction of only frames containing captured lightning strikes from the whole recorded video row, it is suggested to use software based on computer vision library (Open CV).

3. The requirements to characteristics of various MS components are substantiated and possible variants of sensors realizations are proposed (ready products and those that can be designed specially for the MS). The approaches to development of sensors, some related results of simulation and calculations for sensors of electric and magnetic field are included.

There were recommended:

- video cameras – IP-type, 25...50 fps, resolution 1080p or better;
- optical sensor – sensitivity in the range of 0.4...1 μm , time resolution – 1 μs , distance – up to 500 m;
- «slow» electric field antenna – electronic type, without movable parts, 0.1...10 Hz;
- «fast» electric field antenna – rode or plate type, 1 kHz...5 (better – 20) MHz;
- magnetic field registration – compact ferrite antenna, 3...30 (better – 100) kHz;
- thunder recording – capacitor microphones at the frequencies from 0 to 1...2 kHz.

4. Initial experimental laboratory tests are carried out for the optical sensor by using high-voltage impulse current generator. The results confirmed acceptable performance of optical sensor and possibility of registration short-duration (tens of microseconds) light radiation from the discharge channel having impulse current (20...30 kA), which have parameters corresponding to actual typical lightning.

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РАЗРАБОТКА КОНЦЕПЦИИ СИСТЕМЫ МОНИТОРИНГА МОЛНИЙ, КОТОРЫЕ ПОРАЖАЮТ СООРУЖЕНИЯ

Проведен анализ существующих систем мониторинга молний и предупреждения о грозовой активности. Разработана концепция системы мониторинга молний, которые поражают важные сооружения или ударяют вблизи них. В ней используются средства видеорегистрации, датчики (электрического и магнитного поля, светового и звукового сигналов) и компоненты для передачи, накопления и анализа информации по разрядам молний.

Ключевые слова: видеорегистрация молний, мониторинг молний, система мониторинга молний, система предупреждения о грозе.

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DEVELOPMENT OF A METHOD FOR MEASUREMENTS OF THE PARAMETERS OF THE EXTERNAL MAGNETIC FIELD OF TECHNICAL MEANS

На основі моделювання зовнішнього магнітного поля технічного засобу у вигляді сукупності просторових гармонік – мультиполів, розроблено магнітометричний метод вимірювання величин дипольних магнітних моментів. Метод базується на вимірюванні компонент напруженості магнітного поля за допомогою системи із восьми двокомпонентних індукційних датчиків у восьми точках навколишнього простору. Оцінено методичну похибку, надано оцінку ефективності розробленого методу.

Ключові слова: напруженість магнітного поля, дипольний магнітний момент, методична похибка, індукційний датчик.

1. Introduction

At present, the sphere of application of magnetic measurements is constantly expanding. These measurements

are in demand in many fields of science, engineering and industry, such as electric power engineering, design, development and operation of electrical machines and apparatus, space research, navigation, military science, electromagnetic