Results of Full Scale Modeling of Electromagnetic Pulse Impact for Lightning Protection of Power Plants

Vladimir Fortov, Alexei Shurupov,
Valentina Zavalova, Alexander Kozlov,
Mihail Shurupov and Nina Shurupova

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.80560

Abstract

This chapter summarizes the results of experimental modeling of lightning impacts that has been carried out several years on the problem of lightning protection of electric power objects, including power plants, primarily in order to increase the stability of their work. The main purpose of the research is to offer the testing facilities and testing schemes of lightning protection. A feature of the models proposed to the attention is the use of the energy of an explosive magnetic generator (EMG). In the first part of the chapter, the investigation connects with direct lightning current impact. For this purpose, a prototype of mobile testing complex on the basis of an explosive magnetic generator (MTC EMG) was developed. The results of MTC EMG field testing for loads with ohmic resistances of 2–10 Ω in the form of current and voltage pulses are presented. The results of an electromagnetic impulse impact in the near field of lightning were modeled experimentally in the second part of the chapter. As a result, the electrical field strength with a rising of voltage front about 100 ns were up to 500 kV/m, and about 0.2 T/μs of the magnetic induction increasing were obtained in the experiments. The paper provides estimates of the techno-economic analysis of the practical application of the development.

Keywords: power plant lightning protection, modeling of pulse lightning impact, explosive magnetic generator (EMG), electrically exploding conductors (EEC)

1. Introduction

With the development and complication of the structure of the energy facilities, the main problem of electric power industry is to ensure stable operation of power plants and transport of energy to the consumers. In this regard, the role of protection from external influences, especially from lightning, is growing steadily. The numerous experts' statements noted that the ground wires of high voltage line (HVL) supports of stations and cable ways on power plants do not provide the required reliability of the electric grids for the highest voltage classes. Statistics of accidents and breakdowns in the operation of equipment energy indicates a high rate of lightning outages. They ranged from 20 to 50% of the total number of disconnections. The lightning storm outages have negative effect on the station operation, lines, and substation equipment, reducing the switch operational life and causing overvoltage switching on the equipment. Lightning also causes interference in chains of secondary commutation and devices of microprocessor technology, by means of induced electromagnetic fields. Because a lightning refers under the category of natural phenomena which is difficult to study, there is a great interest in full scale modeling effects of lightning. Full simulation of the effects of lightning in some cases is the only source of reliable information on the grounds that it affects on multiple related objects HVL and power plants, as well as to cause nonlinear processes in soils and ground wires when spreading the lightning currents. Understanding of the mechanisms and effects of lightning basic parameters for modeling were taken from work [1].

In the first part of the chapter presents the results of a full scale simulation of lightning currents, affecting directly the grounding devices designed to ensure the safe operation of power facilities. For these purposes have been designed, manufactured, and tested the mobile test complex (MTC EMG). A feature of this complex was the use of a helical explosive magnetic generator (EMG) as a pulse current source. EMG can convert the energy of the explosive in the electromagnetic energy that issues the current pulse in the load. Physical principles of work of explosive magnetic generators are reflected in a lot of classical works. For example, [2] gives the base of physical effects and the methods of generation high level electromagnetic fields. In [3], much attention is paid to EMG with a metal armature, the processes of energy conversion of detonation products into electrical energy pulses, and their efficiency. In [4], various schemes used to connect EMG to loads are discussed. References [5, 6] present the experimental and theoretical work of the Sarov's nuclear center in the direction of lightning simulation using EMG on large grounded objects. EMG using in the experiments to examine spark soil processes [7], allowed us to represent the level of energy and pulse values of generated currents. The ways of transition from theory to practical schemes that use EMG in mobile testing facility were reported by authors in [8] firstly. It demands the reduction of explosive weight that allows realization of EMG, as a consumable item of MTC EMG. The theory of energy transfer from the EMG to high impedance load [9] was used for efficiently transfer energy from the EMG with using transformer circuits. Mathematical modeling of the dynamics of the EMG in a circuit with concentrated parameters allowed choosing the law of inductance output in the operation of EMG to provide a given front of the current pulse in the load without the use of switches. The theoretical background and mathematical modeling of such scheme are described in [10, 11]. In [10], the good agreement of the results of mathematical modeling and experimental measurements is illustrated. This chapter provides more complete results of field tests of MTC EMG. The active inductive load of two types is considered. In the first case, this is the ground loop. In the second case, it is a special model

http://dx.doi.org/10.5772/intechopen.80560

load. The ground loop forms an active load resistance of 2–4 Ω. In the case of the model load, the resistivity is increased to 10 Ω. The results of field tests showed stable reproduction of pulse values of currents at reliability, safety, and mobility of the complex.

The second part of this chapter presents the results of modeling the effects of high power electromagnetic impulse (EMI), disturbing the stability of energy systems. Such impact is not only on the result of a natural disaster—a thunderstorm, but also occurs at the use of electromagnetic pulse weapons and nuclear explosions. The pulse effect of lightning is accompanied by a change in the induction of the magnetic field in time. In this work, the near field of EMI impact was experimentally modeled by means of a source made on the basis of an explosive magnetic generator. The objects of influence were electronic measuring devices used in the experiment and made in a protected design. The front of the pulse current of EMI source was sharpened by a fast key on the basis of electro-explosive conductors (EEC) placed in the load circuit. The regime of rapid explosion was provided by the intense short-term action of the pulse current on the EEC. Reports collected in the chapter [12] are the basis for understanding the physics of the phenomenon of explosion conductors. The theory of explosion of EEC together with similarity criterion reflecting the relationship of mode of energy release in a conductor during the explosion with its physical properties was used in the selection of parameters of EEC [13–20]. As shown in [14, 15], input in EEC energy sufficient for sublimation of conductors was the main requirement. Criterion for the optimal explosion of conductors in the case of capacitive storage as a pulsed energy source was considered in [17]. We used this approach when we started to simulate the explosion of conductors with a pulse source according to the Marx-Arkadyev scheme. The results were reported at the previous conferences on lightning protection [20]. The use of EMG is reported in this chapter. Two experiments were conducted for the same sources. The first experiment was prepared on the basis of preliminary calculations and was a trial one for the second. The measuring and recording equipment includes: control and measuring equipment, including Rogowski coil, voltage divider, oscilloscopes, and high speed camera HX3 of Japanese production for registration of the rapid process of explosion of the EEC. Evidence of a powerful EMI impact on electronic equipment was the fact that none of the devices could not record the data due to the interference and failure except for a specially designed device. This device was designed for other tasks as a recorder of lightning current. In spite of the use of standard means of protection against electromagnetic interference (metal housing grounded at a common point, isolated power supplies, and shielding), the level of exposure was high.

The results of both experimental and theoretical studies of the models presented were presented at conferences on Interaction of Intense Energy Fluxes with Matter, Elbrus, Kabardino-Balkaria, Russia “Elbrus” and Lightning Protection, St. Petersburg, Russia from 2012 to 2018. One of the presentations of the authors can be found on the conference website [20].

The third part of this chapter is devoted to the importance of full scale lightning simulation for lightning protection systems of power plants in terms of technical and economic indicators. The effectiveness assessments are based on the theory set out in the report at the lightning protection conference held in St. Petersburg in April 2018, a reference to the report is in [21].

2. MTC EMG for full scale simulation of lightning currents

2.1. The principles of MTC EMG creation

During the development of the MTC EMG, several technical solutions were tested. The necessary requirements for the complex are: stable reproduction of pulse values of currents, while in operation for high voltage source, mobility, reliability, and safety. In the circuitry of MTC EMG explosive current breaker in the EMG circuit and closer in the load circuit were excluded, as they have essentially nonlinear characteristics and do not allow reproducing pulses of similar energy. The absence of untriggered discharger in the load circuit relieved the voltage jump when the transformer was in no load operation. In the new circuit, the load is always connected to the secondary winding of the pulse transformer (PT), and the EMG is directly connected to the primary winding of the PT. It gives possible to control the voltage on the load, setting the desired mode of operation of the EMG.

The formation of the front of the current pulse was provided by the design of the EMG. Special attention was paid to the geometry of the final section of the generator. The use of conical geometry in comparison with cylindrical geometry leads to an increase in the liner sliding speed. It is important that in these generators, the increase in the speed of the liner sliding along the spiral is achieved not by using a more powerful explosive, but due to the optimal angle of the cone spiral. For matching the EMG and the load, losses in the primary circuit of the transformer and the inductive-ohmic nature of the load were taken into account. Estimates made with the help of an equivalent circuit of substitution [10, 11] made it possible to obtain a condition for minimizing losses in the primary circuit, depending on the parameters of the circuit. At the same time, the efficiency of the energy transfer of the EMG to the inductive-ohmic load began to depend not only on the coupling coefficient of the pulse transformer windings and the ratio of the load inductance and the inductance of the secondary transformer winding, but also on the ratio of the active resistances of the primary and second transformer windings. In such a scheme, shown in **Figure 1**, the energy is transferred into the load both during the operation of the EMG and after completion, and thus, the pulse transformer is actually the storage of electromagnetic energy. In this case, the dissipation of a part of the energy in the primary circuit after the

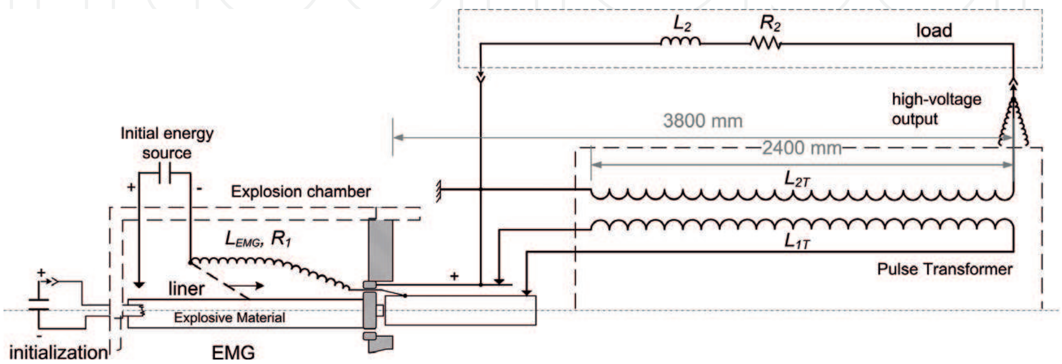


Figure 1. Schematic diagram of the generator of lightning currents with the connected load.

termination of the work of the EMG occurs. Estimates showed that when the condition for minimizing losses in the primary circuit is fulfilled, the efficiency of the transfer of energy into the load may exceed 50%.

MTC EMG is located on two KAMAZ vehicles. The lightning current generator, where EMG is the main element and refers to the spiral type, is mounted on the first four-axle base vehicle. The control panel of the test complex is located on the second three-axle base vehicle. The main elements of the lightning current generator are shown in **Figure 2**.

The most important elements of the lightning current generator are the EMG and the pulse transformer (PT). EMG is placed in an explosive protection chamber, which excludes the destruction of the equipment of the complex during the operation. The explosion chamber is capable of withstanding explosions, which correspond to 5 kg in TNT equivalent. Thus, the EMG is the only consumable element of the MTC EMG. To match the EMG with the load, a pulse transformer with a low inductance primary winding is used. The transformer provides a maximum voltage on the primary/secondary windings of 100/1500 kV and a maximum current in the primary/secondary windings of 5000/100 kA. The transformer ratio is 55. The winding coupling coefficient is not less than 0.95. The design takes into account the requirements for limiting weight and increase in strength. The total weight of the equipment does not exceed 80% of the carrying capacity of the vehicle to ensure cross-country capability. The primary and secondary windings are made on one cylinder. High voltage output is

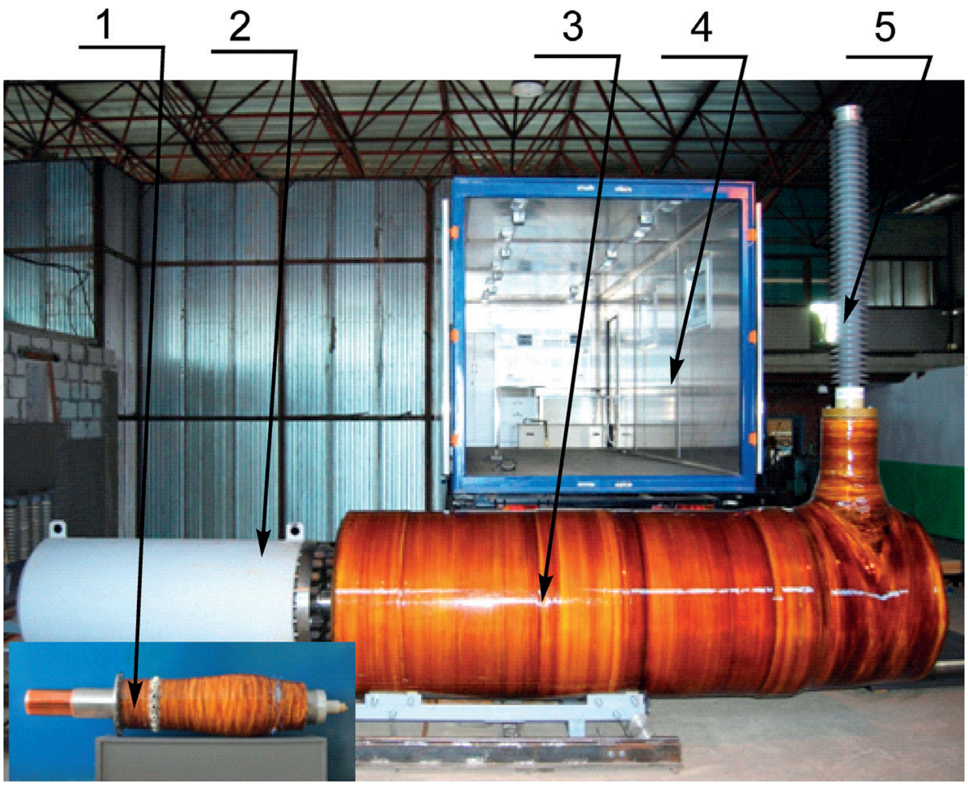


Figure 2. The main elements of the lightning current generator: 1—EMG; 2—explosion protection chamber; 3—pulse transformer; 4—container body; 5—bushing insulator.

carried out through a bushing insulator with a height of about 3 m. The commands between the control panel and the lightning current generator are transferred via fiber-optic communication lines. The measuring complex consists of self-contained recorder oscillograph. Recorders have autonomous power supply and are in a shielded enclosure. The recorder can be placed under any potential.

Most technical solutions are patented. In this scheme, a capacitive storage of electric energy is used as an initial energy source for creating an initial magnetic field in the EMG with an energy of up to 100 kJ. The initialization system is designed to initiate an explosive charge in the generator. The system does not contain electric detonators, which significantly increases the safety of work with explosives.

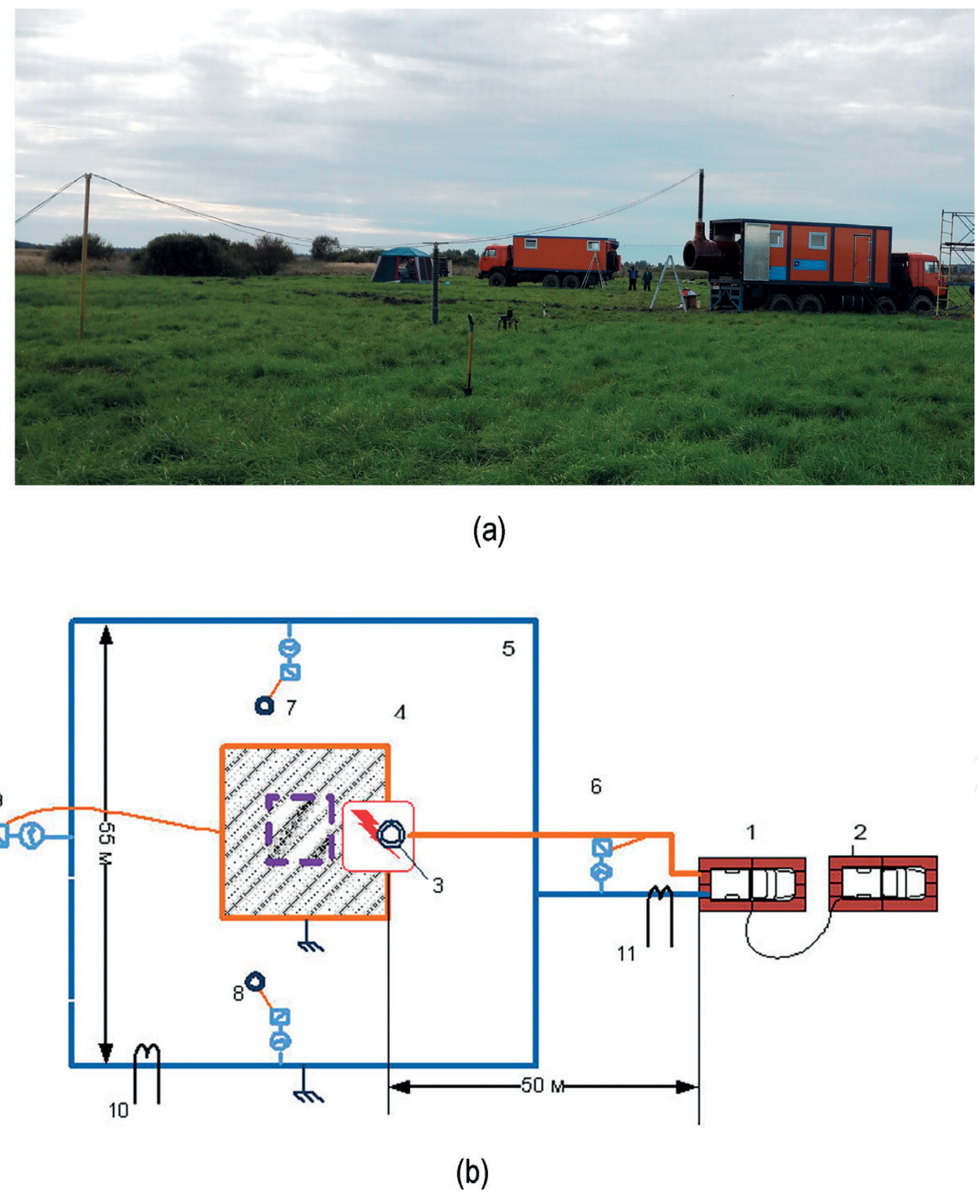


Figure 3. Photo of field tests (a) and experimental diagram (b). 1—lightning current generator; 2—control machine; 3—impulse current input rod; 4—internal input circuit (dashed for the 2nd experiment); 5—ground loop; 6–9—voltage dividers; 10 and 11—Rogowski coils.

2.2. The results of the field tests of the MTC EMG on the ground loop

Field tests for an active load of up to 4 Ω were carried out in the east of the Moscow region. The test stand was located on the territory of approximately 70 m × 70 m. The photo of the placement of the MIK VMG and the experimental diagram are shown in **Figure 3**. The load was the ground between two ground loops. Ground loops were made of an aluminum wire with a diameter of 10–12 mm, located at a depth of 0.5 m. The external ground loop was 55 m × 55 m square. The internal ground loop in the first experiment was 15 m × 15 m, which corresponded to a load resistance of 2 Ω, in the second—4 m × 4 m (load resistance—4 Ω). The current was transmitted from the MTC EMG insulator mast to the pulse input rod into the internal circuit via the current transmission line. The total inductance, taking into account the air transmission line, did not exceed 80 μH.

During the tests, the following parameters were recorded: initial current (powering current) of the EMG, current of the EMG (current of the primary winding of the PT), current in the load (current in the secondary winding of the PT), voltage at the MTC EMG output, that is, on inductive-active load, and voltage on the active load.

Rogowski coils were designed to record the derivative of current. They were used without integrators. The current was calculated by software integration of the data, taking into account the sensitivity of each coil. Voltage dividers were used to measure the voltage. The first voltage divider was connected to the high voltage output of the MTC EMG. The second voltage divider was connected to the load. To improve the transient characteristics, low inductance carbon resistors with a total resistance of 20 kΩ were used, which were located in a fiberglass pipe filled with transformer oil. To reduce the effect of parasitic capacitance of the resistor to the ground, when measuring, a pulsed current transformer on a ferrite core with a transformation ratio of 1:55 was used in a divider. This gave a galvanic isolation between the secondary circuit with the oscillograph and the primary circuit with the measured signal. Output voltage ratio was 1:220,000 (~1 MV:5 V).

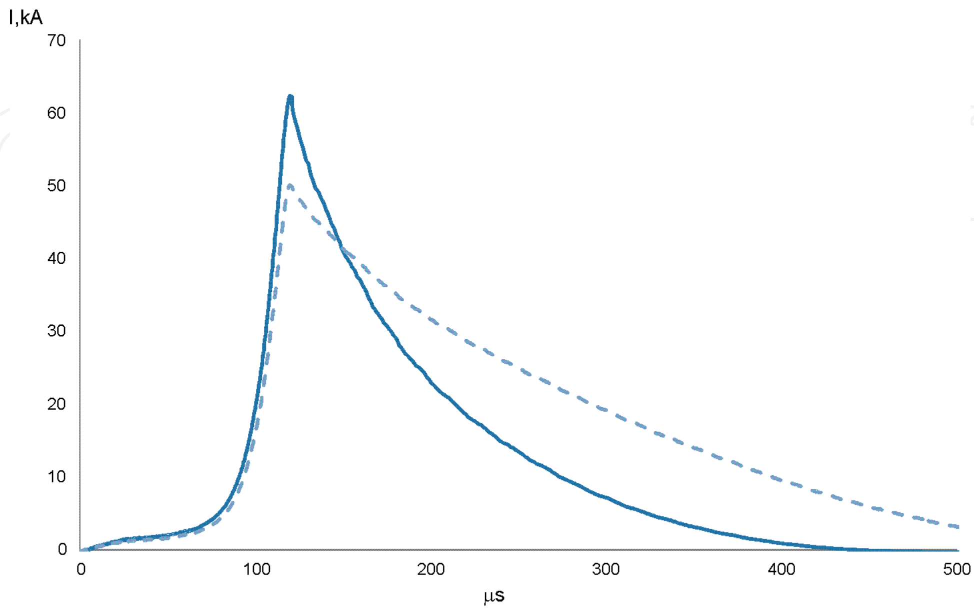


Figure 4. The measured values of the currents in the load for the 1st (dotted line) and 2nd experiments.

Measurement of the resistance of the load (ground) was carried out before the beginning of the experiments. It is assumed that the potential of the outer loop due to its low resistance is zero. This assumption is satisfied (with an accuracy of 0.5%) for the experiment with an internal contour of 4 m × 4 m (experiment no. 2) and about 7% for an internal contour of 15 m × 15 m (experiment no. 1). The main results of the two tests (experiments) are presented in the graphs of **Figures 4** and **5** and in **Table 1**.

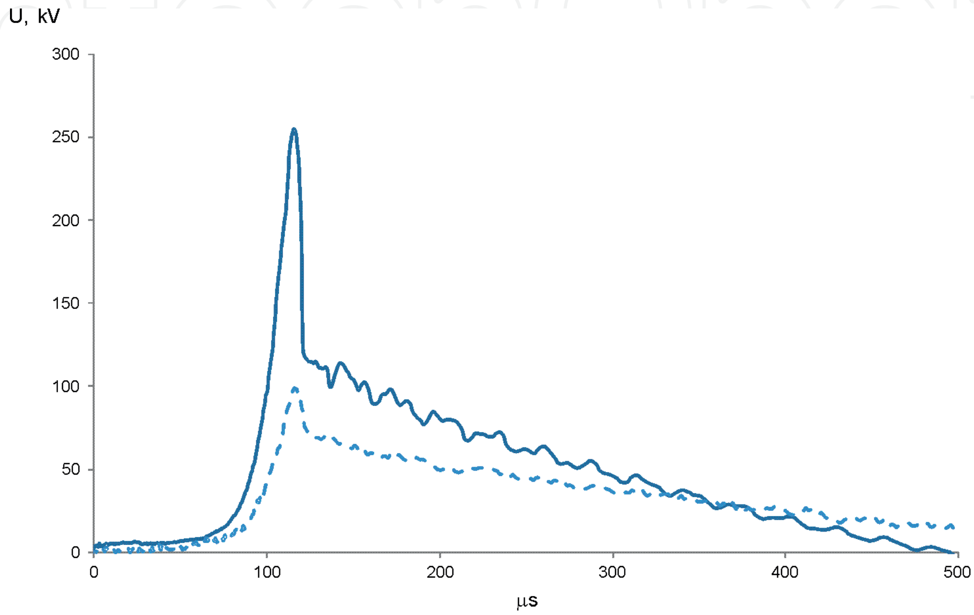


Figure 5. The measured values of the voltage on the load for the 1st (pale color) and the 2nd experiments.

Parameters/experiment no.	No. 1	No. 2
Initial resistance between current input circuits (active load), Ω	2	4
Load inductance, µH	75	86
Initial energy of EMG, kJ	23	43
Maximum amplitude of the current in the load, kA	50	63
Energy generated by EMG, kJ	900	1500
The maximum amplitude of the output voltage of MTC EMG, kV	220	450
Maximum amplitude of the active load voltage, kV	100	250
Rise time of the current pulse, µs	30	25
Half-amplitude duration of the current pulse, µs	120	80
Energy dissipated in the active load, kJ	500	800
The increase in energy (energy in the active load with respect to the initial energy of the EMG)	21	20

Table 1. Parameters registered in the experiments.

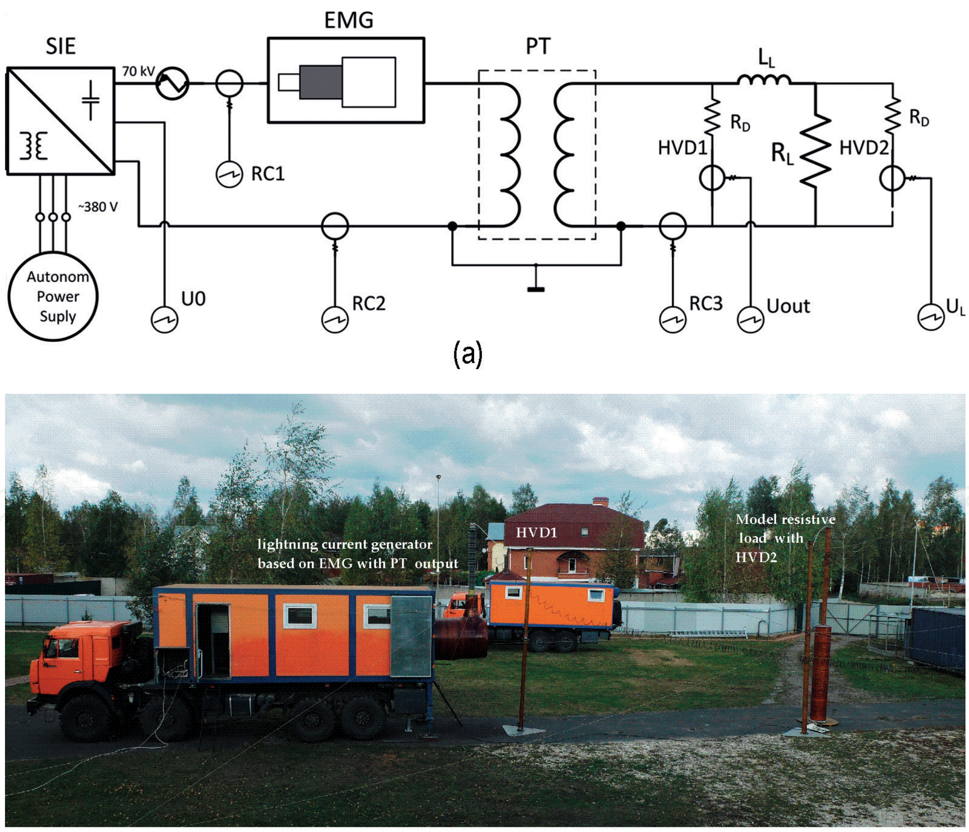
http://dx.doi.org/10.5772/intechopen.80560

Tests of the MTC EMG on the ground loop in the configuration, when the current flowed in the ground between the outer and inner contours, showed a linear increase in the voltage on the load with a decrease in the dimensions of the inner contour. A further increase in the load resistance in the tests became possible when the experimental scheme was changed and the use of model resistance.

2.3. Results of field tests of MTC EMG on model load

MTC EMG field testing on the terminal parameter of the load specified in the development was carried out on a model load with an active resistance of 10 Ω and an inductance of about 150 μH. The tests were carried out on the territory of JIHT RAS, Shatura, Moscow region. Scheme and photo of the experiment are presented in **Figure 6**.

Figure 6a shows a diagram of the connection of the model load to the lightning current generator via a pulse transformer, as well as the location of the Rogowski coils for measuring currents and voltage dividers for measuring the voltage in the circuit. A model load has been developed and manufactured specifically for testing. The active load was modeled by a 10-Ω noninduction resistance.



(b)

Figure 6. Scheme (a) and the photo (b) of the experiment for model load. SIE—source of initial energy with a capacitive storage; PT—pulse transformer; R_L—resistive (active) load; L_L—inductive load; RC 1… RC 3—Rogowski coils; HVD 1, HVD2—high voltage resistive dividers (1000 kV).

In the foreground of **Figure 6b**, there is a lightning current generator on the first vehicle, on the left—an active load (a noninduction resistor) and two voltage dividers: at the MTC EMG output and on the load. In the background, there is the second vehicle with the control panel.

Parameter	Value
Active load resistance, Ω	10
Load inductance, μH	150
Voltage of the source of initial energy, kV	62
Amplitude value of the powering current, kA	115
The initial energy of the EMG, kJ	73
The maximum derivative of the EMG current, kA/μs	310
The maximum amplitude of the EMG current, kA	6010
Energy generated by EMG, kJ	900
The maximum amplitude of the voltage at the MTC EMG output, kV	810
Maximum amplitude of the voltage on the active load, kV	495
Maximum amplitude of the current in the load, kA	44
The energy produced by the MTC EMG, kJ	1640
Energy dissipated in the active load, kJ	550
The increase in energy (energy in the active load with respect to the initial energy of the EMG)	7
Rise time of the current pulse, μs	37
Half-amplitude duration of the current pulse, μs	50

Table 2. Basic parameters in the tests for model load.

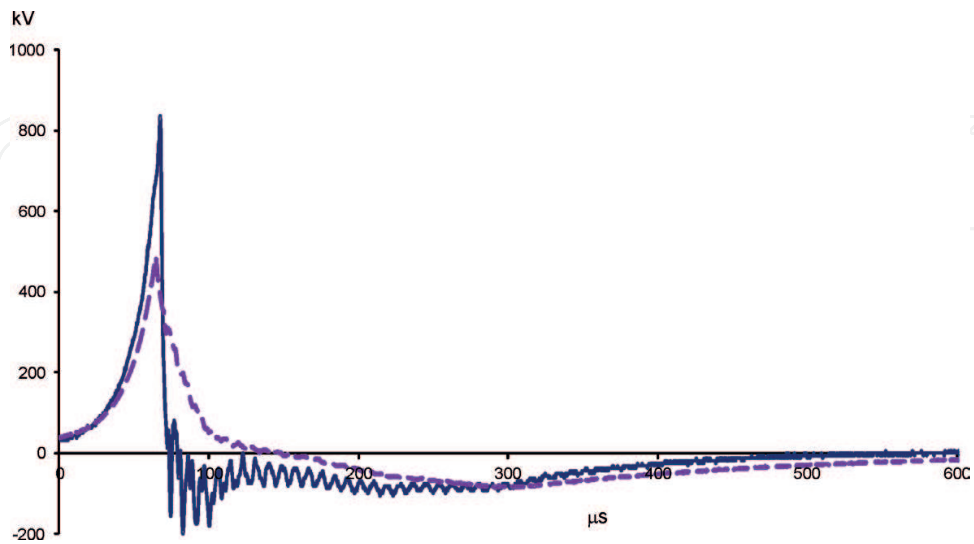


Figure 7. Voltage at the MTC EMG output from the voltage divider no. 1 and on the active load from the voltage divider no. 2.

Resistance was installed vertically. The inductive load was modeled by wires connecting the resistive load. To reduce the size, the high voltage connection of the wire for the active load was made in the form of a spiral.

The main results of tests for the model load are presented in **Table 2** and in the graphs of **Figures 7–9**. In these experiments, the signals were recorded on single-channel autonomous oscilloscopes; recording was performed at a given level of the input signal, which explains the time shift of the graphs relative to zero.

As can be seen from **Tables 1** and **2**, the increase in the active load resistance leads to a decrease in the energy transfer efficiency of the load from 55 to 33%, which corresponds to the theory [10, 11]. Thus, the use of MIC HMG for high resistance loads is less effective.

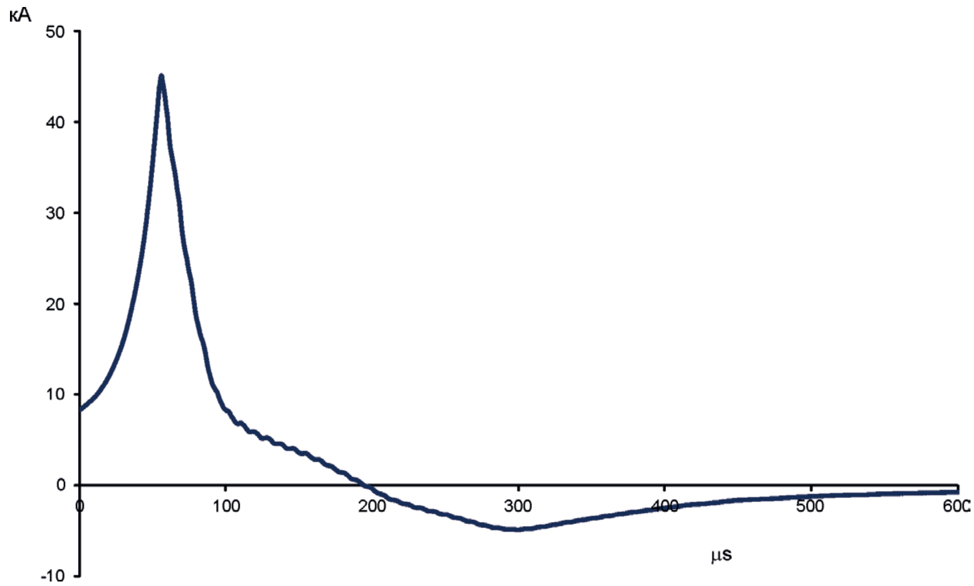


Figure 8. Load current.

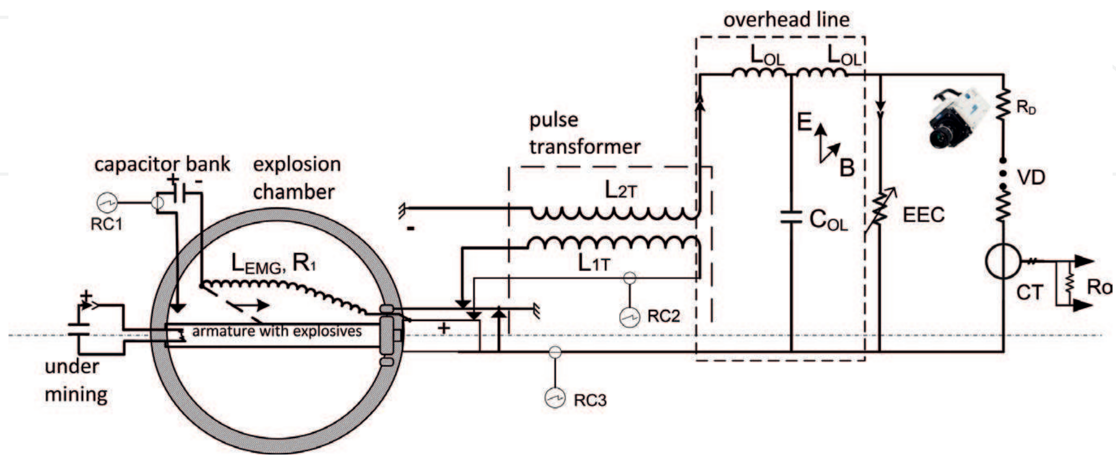


Figure 9. Schematic diagram of an experimental model with a power source based on the EMG. C_{OL} and L_{OL}—are the capacitance and inductance of overhead line; RC1—Rogowsi coil in the EMG circuit; RC2—Rogowsi coil in the load circuit; CT—the current transformer as part of voltage divider.

3. Simulation of electromagnetic pulse effects

3.1. Problem statement

The pulse effect of lightning is accompanied by a change in the induction of the magnetic field in electrically conductive objects in time. The induction effect of the lightning channel is significant at distances commensurate with the length of the lightning channel. Induced voltages arise as a result of such influence on various technical means, for example, overhead transmission lines, grounding devices, etc. Induced voltage leads to the appearance of parasitic currents in the secondary circuits and external power cables due to the conductive coupling. The experimental model based on the EMG is a laboratory setup producing EMI impact on a limited space of 2 m × 2 m × 4 m. The schematic diagram of the electrical control and measuring equipment is shown in **Figure 9**.

The source of the pulse current is a helical-type explosive generator—EMG also. Output of current to the load is carried out through a pulse transformer (PT) and overhead transmission line (OL). The direct and reverse branches of the overhead lines are located on the insulator supports and are common for all experiments. The electrical explosion conductors (EEC) are at the end of the overhead line. General view of an experimental model is represented in **Figure 10**, and the view of EMG assembly is represented in **Figure 11**.

EEC in the EMI models is the key element. The regime of fast explosion is provided by the intense short-term action of the pulse current generated by the source. The rapid increase in resistance in exploding conductors leads to arising of a strong electric field. Together with the

Figure 10. General view of an experimental model with EMG.

emerging magnetic field, an electromagnetic disturbance is formed by the EMI effect. The EEC in our models was made from the copper. Copper has a relatively low boiling point and low heat of vaporization. The current reaches the maximum by the end of evaporation if sufficient energy is supplied to the conductor [11]. The selection of EEC parameters, as the number, cross section, and length of the EEC, was carried out taking into account the similarity criteria reflecting the relationship of the character of the energy release in the explosion in the conductor with its physical properties. At the initial stage, the estimates were performed according to the criterion for capacitive energy sources set out in [16], but due to the difference in the pulse current fronts, they were overestimated in terms of the energy required for the explosion of conductors. The main criterion is the ratio of the transmitted EEC energy to the mass of the explosive conductor, which characterizes the initial stage of the explosion. From the balance of the inputted energy and the minimum specific energy required for the explosion, it is possible to estimate the limit mass of the conductors $m = (W_0/\tilde{w})$, where W_0—inputted energy, J; ρ_{cu} —copper density; $\tilde{w} \sim \tilde{w}_m + \tilde{w}_s$, $\tilde{w}_m$—specific melting energy; $\tilde{w}_s$—specific heat of sublimation for copper. Properties of substances were taken from the directory [18], $\tilde{w}_m = 2.13 \cdot 10^5$ J/kg, $\tilde{w}_s = w_v/\rho_{cu} = 5.28 \cdot 10^6$ J/kg ($w_v = 4.7 \cdot 10^{10}$ J/m^3), where w_v is the amount of heat required to convert a unit volume of the conductor material into a metal vapor consisting of neutral atoms. In this regard, the energy $\tilde{w}$ can be interpreted as the minimum specific energy of electrothermal destruction of the conductor material. For a source with a capacitive storage, W_0 is its initial energy, which corresponds to the current action integral calculated for the first quarter of the period. For a source with EMG, W_0 was estimated from the produced energy of EMG, taking into account the efficiency of transmission through the transformer to the load and corrected from the integral of the current action in the load. The total cross section of the conductors was calculated from the energy balance and was associated with the integral of the current: $S_{sum} = \sqrt{(I_d \cdot \rho_e/\tilde{w}/\rho_{cu})}$, where $I_d = \int_0^t I^2(t)dt$—action integral, where ρ_e is the electrical resistivity, which was taken at the melting point. The current in the load for the first experiment was initially modeled numerically; it was supposed that the conductor is torn at the maximum value of the current. Further, the rate of input of the critical energy density in the adiabatic approximation

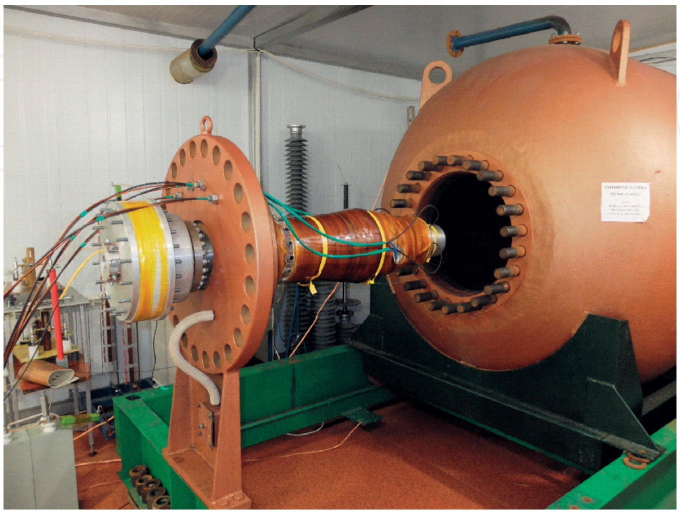


Figure 11. EMG assembly, before installation in the explosion protection chamber.

is estimated $dW/dt = j_C^2 \rho_e$, W/m³, $j_C \sim 3.4 \cdot 10^{11}$ A/м², critical current density for copper conductor [3, 11]. The time scale of the explosion of the copper conductor was estimated from the law of conservation of momentum (the equation of motion taking into account the equation of state, at equilibrium of the liquid and gas-plasma phase). Thus, the estimated time of the explosion corresponded to the value of $\tau_в \sim r_0\sqrt{(\rho_c/p_c)}$, where r_0 is the radius of a conductor and ρ_c and p_c are the density and pressure at the critical point. For copper $\rho_c = 2.27 \cdot 10^3$ kg/m³, $p_c = 9.04 \cdot 10^3$ atm [18], for conductors 80–120 μm, the time was about 80–110 ns. As shown by experiments, the preliminary calculation gave higher values of the integral of the current than in practice. This was because the front-of-the-model current was steeper. Therefore, two experiments with the same initial energy were carried out. The first experiment was trial for the second one. The analysis of the results of the first experiment allowed us to specify the parameters of the node of the pulse exacerbation in order to control the formation of the voltage pulse.

3.2. Results of laboratory experiments

We use the initial energy source for powering the EMG, it was about 15 kJ (a capacitor bank of 90 μF was charged to 18 kV). An overhead line inductance was 5.5 μH.

In the first experiment, 25 conductors of 120 μm diameter were taken. The full cross-sectional area of the conductors is $28 \cdot 10^{-8}$ m². The total mass of all conductors amounted to about 2.5 g. The number of conductors was determined by the requirement to obtain an explosion of conductors at the stage of current growth in the load. The specific energy obtained by the conductors is 12.5/2.4–5.2 kJ/g; it is roughly equal to the energy of the sublimation of copper. The experiment showed, see **Figure 12**, that the current was cut off (and the voltage increased abruptly) at the initial phase of the current rise. The current pause mode does not occur, and

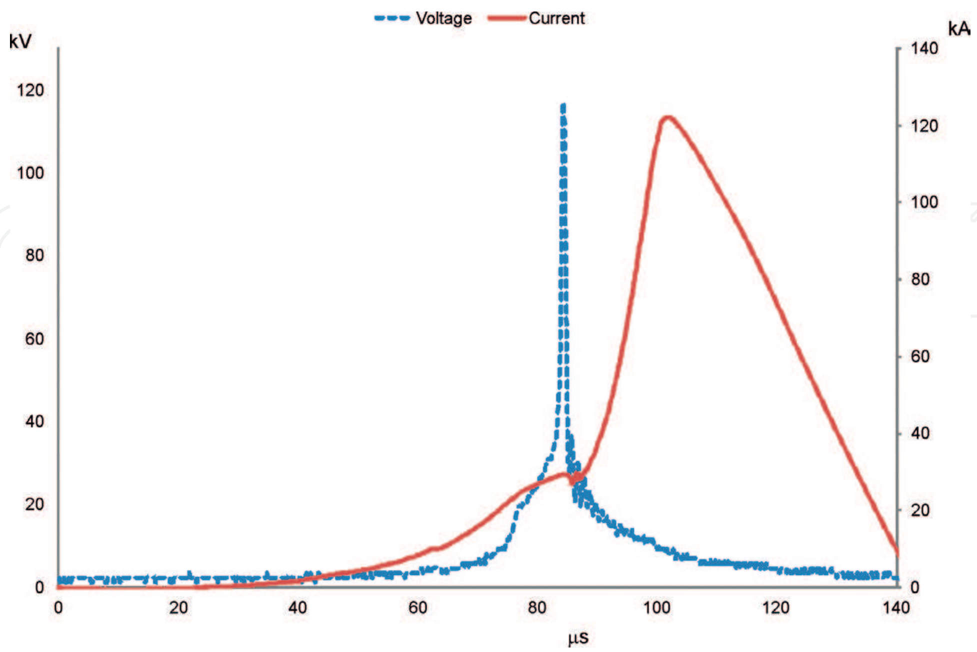


Figure 12. Impulse current and voltage values obtained with the explosion of conductors in the 1st experiment.

http://dx.doi.org/10.5772/intechopen.80560

the further increase in the current is associated with the transition of the EEC into an electrically conductive plasma state. To achieve higher voltage amplitudes, we need to input more energy. This meant that we need to climb higher along the current curve to the time of the explosion of the EEC. To do this, we need to take more conductors, for input more energy, with a smaller diameter of each to increase the speed of energy input.

In accordance with the described reasoning, in the second experiment, 96 copper conductors with a diameter of 80 μm were taken. The total area of the cross sections of the conductors is $48 \cdot 10^{-8}$ m^2. The total mass of all conductors was about 4.3 g. The initial charging voltage was chosen as in the previous experiment, ~18 kV, respectively, the initial energy was about 15 kJ, as in the previous experiment. The explosion of the EEC occurred at 92 μs, which corresponds to the current drop and voltage peak, as illustrated in **Figure 13**. The maximum value of the current in the explosion was about 70 kA. In the current distribution, see **Figure 13**, we see again a nonpause mode of EEC transition into an electrically conductive plasma state. Further, the current increases again after several periods of high frequency oscillations to a maximum value of 127 kA, **Figure 13**. Then the plasma conductivity decreases due to the expansion of the plasma column, and the current begins to fall. Voltage amplitude at the moment of explosion was about 550 kV, and the electric field strength was about 550 kV/m. Voltage peak occurred approximately 0.5 μs after the explosion of conductors. The front of the voltage pulse was estimated to be approximately 100 ns. Estimates of the current density in the explosion gave a value of about $3 \cdot 10^{11}$ A/m^2. The resistance growth rate was about 16 Ω/μs. The energy inputted in the EVP during the explosion is about 60 kJ. Specific energy was 60/4.3–14 kJ/g, approximately 2.7 times more of sublimation energy of a copper.

Characteristics of high speed camera Memrecam HX-3 (16 Gb, exposition time—200 ns, frame rate of 750,000 frame per second at working special resolution 320 × 24) allowed to fix the

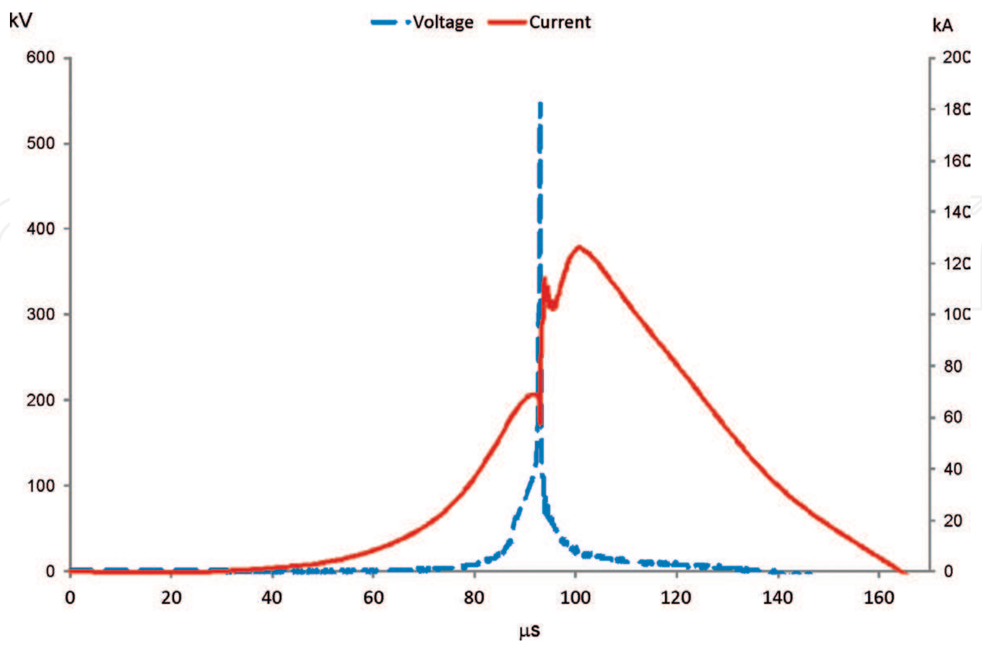


Figure 13. Experimentally obtained impulse current and voltage at the load (EEC).

time of the explosion. Three frames, shot one after another, include: the first frame—before the explosion, the middle frame clearly illustrates the locally glowing area of the exploded conductor, and the next frame—a glowing plasma column formed by the products of the explosion of the EEC. The column has a radius much exceeding the initial radius of the wire, **Figure 14**. The split of the image is connected with the re-reflection from the neighboring conductors. Displayed glow significant attenuated on one-hundredth the frame that corresponds to time over 130 μs after the explosion (~220 μs). At this time, the current almost disappears.

The change of magnetic induction occurring around the EEP at the moment of break was estimated from the Ampere law in the approximation of a single turn solenoid, (N = 1), $\frac{\partial B}{\partial t} = \frac{\mu 0 \cdot N}{2 \cdot \pi \cdot r_{OL}} \cdot \frac{\partial I}{\partial t}$, where *μ0* is the magnetic constant and r_{OL} is a half-height of OL. The maximum value of the current derivative at EEW break was about 170 κA/μs that gives a value of abo ut $\frac{\partial B}{\partial t} = -0.2\text{T}/\mu\text{s}$. The successful use of special devices that measure pulse current at the EMI effect was demonstrated and the obtained curves represented in **Figure 15**. These devices are a new generation of self-contained oscilloscope recorders used for the first time in the

Figure 14. Average frame illustrates of EEC explosion. The top frame is before the explosion and the bottom after the explosion.

Figure 15. Photo of the device for registration of current derivative from the source of powerful EMI action in the near field based on the 4th generation lightning current recorder.

measuring equipment of the MTC EMG. Then, they were modified to register the currents of a multicomponent lightning. They have been successfully tested on 220 kV power lines of main electric networks of the South of Russia. In the conditions of strong level of electromagnetic interferences, devices reliably record current derivative and voltages, followed by playback and processing of data on the computer. Analog-to-digital data conversion is 12 bits. The duration of data recording for each component of the lightning current is 600 μs. The temporal resolution of the recorded data is about 100 ns. Further application of this registrar in this research area will be accompanied by an increase in its temporary resolution.

4. Techno economic analysis of the effectiveness of the application of models

There is not a ready-made model of techno economic analysis of the creation project of commercial samples of testing complexes for lightning protection tasks. We took as a basis of the economic expediency of the introduction of system of lightning protection from the point of view of minimizing outages caused by lightning. The analysis is based on the idea of calculating the internal rate of return (IRR) of the protection method, as well as the data on lightning outage presented in the report [21], University of S. Paulo, Brazil. The main numerical indicators for economic calculations and the list of lightning protection services are close to the Russian market. The methodology is based on an analysis of the cost of lightning protection and the benefits of lightning protection. The benefit was regarded as an opportunity to save on the damage caused by the emergency situation both at the power plant itself and the damage caused by the delay in the supply of electricity to consumers, including the payment of fines for regulated direct and indirect losses. It was taken into account what can be represented in monetary terms, excluding social and moral aspects. The simplified calculation did not take into account such aspects as: loss of communication, information, Internet access, reduced mobility of the population, damage to frozen products, disruption of banks, state institutions, etc. The main costs are the measures used to increase the lightning resistance of power plants. These include the improvement of insulation resistance, the use of earthed shielded cables, the installation of arresters in distribution networks, as well as the installation of grounding devices that carry out the removal of lightning currents into the ground. The volume of storm shutdowns was considered as a total number of cases and also with respect to areas with different population densities. Different protection systems with different degrees of complexity were considered. The average costs and benefits for each system were reduced to a unit of time. The obtained input data allowed estimating the values of cash flows and calculating the IRR for each protection system. This rate is equal to the ratio of profit (the amount of losses that can be avoided) to the amount of costs (investments). The following conclusions are made:

- The lightning protection project is effective and appropriate if the final IRR rate is higher than the minimum rate of return for long-term financing, and for Russia, it is about 7% per annum. That is, the energy distribution company should have a positive return on investment.
- Developing countries, where the cost of capital is high, face great difficulties in investing in protection systems, especially in regions with low population density and low income.

If we continue the study of technical and economic analysis in accordance with the proposed methodology in relation to the effectiveness of the implementation of the development of testing systems for our project, we can add the following conclusions:

- We get the amount of benefits for the development of integrated solutions. Each benefit from the selected protection measure can be tested separately. And most importantly, it is possible to get the best comprehensive solution in the application of several protection measures. In theory, such solutions are difficult to obtain because the overall protection solution is not simply the sum of individual measures. For example, for grounding devices that perform the removal of lightning currents, to minimize the resistance of multipath grounding, it must take into account the specific resistance of the soil.
- Developed complex solutions based on the tests can be standardized according to the adopted standards of protection and reproduced in the form of ready-made solutions.
- By using testing complexes in the construction of power plants or scheduled safety inspections, it is possible to reduce the safe level of overvoltage and, accordingly, the number of lightning outages.
- The creation and use of such test complexes are of high importance for developed countries, which have a high level of requirements for the operation of power plants, namely, to the quality and continuity of the energy supplied by them.

The cost of MIC EMG, without the option of EMI impact analysis, is approximately $ 2.3 million per 1 MJ of energy, which is transferred to the load. The evaluation was performed in 2017. As a result of R & D, a sample of testing complex, laboratory test stands, and a set of design and technological documentation necessary for the transition to commercial samples were obtained.

It should be noted that the test complexes based on EMG are a means for testing the existing protection of power stations from lightning. Despite the fact that the basis of EMG work is the physic-chemical law of conversion of chemical energy explosives into electrical energy with an efficiency of not more than 10%, and this tool is able to generate pulsed currents of the mega-ampere level and the electric field intensity of MV/m per microsecond, not achievable by other methods. In the transition from R & D to commercial facility, it requires a detailed calculation, first of all, of the technical and economic effect of the use of testing complex. The powerful impact of lightning is a probabilistic process for the power plant, but the level of destruction is much higher than any other losses. To calculate this effect, it is necessary to take specific parameters to improve lightning protection, applying to the technique described in work [22, 23], and calculate energy and exergy efficiencies. The return on investment in such complexes is likely to be correctly compared with the level of return on capital from long-term investments. There is a direct connection with the economic development of the country, which can afford high tech equipment.

5. Conclusion

Field tests of MIC EMG demonstrated stable reproduction of pulse values of currents during operation: its mobility, reliability, and safety. For the range of loads with active resistance from

1 to 10 Ω and inductance of 70–150 μH, the amplitude values of the currents ranged from 70 to 40 kA. Thus, the efficiency of application of MIC EMG for modeling lightning currents at low resistance loads such as grounding at electrical substations and power plants has been confirmed. The practical application of MIC EMG will allow increasing the level of lightning protection of strategically important energy facilities both at the stage of their building construction and during preventive inspections.

Laboratory testing of the generator of powerful EMI impacts on the basis of the EMG and electro explosive conductors in the load circuit confidently registered voltage pulses with the front of about 100 ns and the amplitude of the electric field strength of about 500 kV/m. The growth rate of the magnetic field intensity in the near field reached 0.2 T/μs. In practice, the use of such a facility will allow to solve the problem of optimizing the location of the elements of grounding devices in order to equalize the potentials in the grounding systems and to identify parasitic connections in electrical circuits, including those induced in the secondary circuits of underground utilities.

The tests of the described system samples showed the readiness of the development for the transition to commercial development. This chapter of the techno economic analysis of the development provides an approach to assess the profitability of the complex depending on the location of the power plant and the required level of lightning protection.

Author details

Vladimir Fortov, Alexei Shurupov, Valentina Zavalova*, Alexander Kozlov, Mihail Shurupov and Nina Shurupova

*Address all correspondence to: zavalova@fites.ru

Joint Institute for High Temperatures of the Russian Academy of Sciences (JIHT RAS), Moscow, Russia

References

[1] Bazelyan EM, Raizer YP. Physics of Lightning and Lightning Protection. Moscow: Fizmatlit; 2001 (in Russian)

[2] Knoepfel H. Pulsed High Magnetic Fields. Amsterdam: North-Holland; 1970

[3] Fortov VE. Explosive Generators of Powerful Pulses of Electric Current. Moscow: Nauka; 2002 (in Russian)

[4] Altgilbers LL, et al. Magnetocumulative Generators; 2000. DOI: 10.1007/978-1-4612-1232-4

[5] Vilkov YV, Kravchenko AS, Saitkulov MM, et al. Instruments and Experimental Techniques. 2012;**55**:580

[6] Vilkov YV, Kravchenko AS. Instruments and Experimental Techniques. 2006;**49**:523

[7] Vilkov YV, Kravchenko AS, Selemir VD, Terehin VA. Instruments and Experimental Techniques. 2011;**54**:375

[8] Shurupov AV, Dudin SV, et al. In: Proceedings of the 12th International Conference on the Generation of Megagauss Magnetic Fields and Related Experiments; 13-18 July 2008; Novosibirsk. 2008. p. 298

[9] Herlach F. Explosive-driven energy generators with transformer coupling. Journal of Physics E: Scientific Instruments. 1979;**12**(5):421-429

[10] Shurupov AV, Kozlov AV, Zavalova VE, Bazelyan EM, et al. Mobile testing complex based on an explosive magnetic generator. Journal of Applied Mechanics and Technical Physics. 2015;**56**(1):158-165. DOI: 10.1134/S002189441501023X

[11] Shurupov AV, Kozlov AV, Zavalova VE, Shurupov MA, Fortov VE. The sources of pulse current based on explosive magnetic generators for mobile testing facility. IEEE Transactions on Plasma Science. 2016;**44**(10):1956-1960. DOI: 10.1109/TPS.2016.2566929

[12] Chace WG, Moore HK. Exploding Wires. New York: Plenum Press; 1962

[13] Oreshkin VI, Barengol'ts SA, Chaikovsky SA. Numerical calculation of the current specific action integral at the electrical explosion of wires. Technical Physics. 2007;**52**:642-650

[14] Borisevich SL, Cherkas SL. Technical Physics. 2012;**57**:1380-1386

[15] Pikuz SA, Tkachenko SI, Barishpol'tsev DV, et al. Technical Physics Letters. 2007;**33**:651-654

[16] Khishchenko KV, Tkachenko SI, et al. International Journal of Thermophysics. 2002;**23**:1359-1367

[17] Khainatskii SA. Condition for realization of an optimum regime of the electric explosion of conductors in liquid media. Technical Physics Letters. 2009;**35**:299-301

[18] Grigoryev IS, Meilihov EZ. Fizicheskie Velichini: Spravochnik. Moscow: Energoatomisdat; 1991 (in Russian)

[19] Bushman AV, Fortov VE, Kanel' GI, Ni AL. Intense Dynamic Loading of Condensed Matter. Washington: Taylor & Francis; 1993

[20] Zavalova VE. Results of Electromagnetic Pulse Impact Simulation for the Purpose of Energy Facilities Lightning Protection [Internet]. 2018. Available from: http://en.rclp2018.com/presentations/

[21] Bernal PSM, Piantini A, Parente V. Cost-Benefit Analysis of Lightning Protection Systems in Distribution Networks [Internet]. 2018. www.rcgi.usp.br. Available from: http://en.rclp2018.com/upload/iblock/a30/a30575f09c84c12796cd2e47ba331d9f.pdf

[22] Taner T, Sivrioglu M. Energy-exergy analysis and optimisation of a model sugar factory in Turkey. Energy. 2015;**93**(1):641-654

[23] Taner T, Sivrioglu M. A techno-economic & cost analysis of a turbine power plant: A case study for sugar plant. Renewable and Sustainable Energy Reviews. 2017;**78**:722-730. DOI: 10.1016/j.rser.2017.04.104