Experimental investigation of powerful pulse current generators based on capacitive storage and explosive magnetic generators

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Abstract. Experimental models of microsecond duration powerful generators of current pulses on the basis of explosive magnetic generators and voltage impulse generator have been developed for the electromagnetic pulse effects on energy facilities to verify their stability. Exacerbation of voltage pulse carried out through the use of electro explosive current interrupter made of copper wires with diameters of 80 and 120 µm. Experimental results of these models investigation are represented. Voltage fronts about 100 ns and the electric field strength of 800 kV/m are registered.

1. Introduction
An important task of the power industry is ensure the stable operation of power systems at electromagnetic pulsed impact (EMP). EMP impact arises not only due to targeted technological factors but also natural, such as lightning, and is a cause of malfunction or failure of electrical and electronic equipment. EMP impact can lead to occurrence of overvoltage in electrical circuits; induced currents in the secondary circuits of conductive connections, including cables to an external power supply and output of information; generate electromagnetic blast in microelectronic technology. It is known that the breakdown voltage microelectronic elements are low and range from a few to tens of volts, depending on the device type. Electromagnetic blast or penetration of energy through the design holes and joints depends on their size and the wavelength of the electromagnetic pulse. The strongest relationship occurs at the resonant frequencies, when the geometric dimensions comparable with the wavelength.

Creating facilities for full-scale modeling of EMP effects is a necessary step for further progress in the task of ensuring the stable operation of power systems. Full-scale modeling facilities of EMP impact require the creation of models of high-power current pulse generators. This report presents the development of models powerful generator of microsecond duration of the current pulses on the basis of explosive magnetic generators (EMG) (or the same, magneto cumulative generators) and capacitive storage, as well as the results of experimental studies of these models. For pulse front exacerbation (up to the order of hundreds of nanoseconds) is used the current interruption in the load by the parallel electro-exploded wires (EEW).
Theoretical basics of EEW in the circuit with sources of voltage and current are presented in [1–4]. A special feature of EEW is its small cross section (diameter is several tens μm) that provides the resistance increasing of share of ohm per a nanosecond at the high-energy pulse input and allows to achieve critical current density level $10^{11}–10^{12}$ A/m$^2$. Explosion EEW leads to the current derivative increase, which is the reason of the high voltage amplitude on its own circuit inductance up to MV-level during 100 ns. Voltage (or the electric field strength) jump also induces corresponding magnetic induction (magnetic field strength) in the test volume.

Start of work on the creation of stands and model experiments with a storage capacitor of 25 kJ were presented earlier in [5]. This report describes the use of two types of pulsed sources. The voltage pulse generator (VPG) according to the scheme of Marx was used as a storage capacitor. EMG of spiral type forming the output pulse current with amplitudes of the order of several MA, was an alternative source.

2. EMP impact mechanism in models and preliminary estimates

EEW models are a key element in EMP impact. Rapid explosion mode provides intensive short-term effect of pulsed current, generated sources. The rapid increasing resistance in the exploding conductor leads to a strong electric field. Together with the magnetic field arising in the load formed electromagnetic field we get EMP impact. We use the copper conductors as EEW. Copper has a relatively low boiling point and heat of vaporization. The current reaches the minimum energy required for an explosion, we can estimate the weight limit of wires $m = W_0/\tilde{w}$.

Where $W_0$ is the energy inputted to the wires, $J$; $\tilde{w} = \tilde{w}_m + \tilde{w}_s$, $\tilde{w}_m$ is the specific energy of melting, $\tilde{w}_s$ is the specific energy of sublimation for copper. Properties of substances were taken from [10], $\tilde{w}_m = 2.13 \times 10^5$ J/kg, $\tilde{w}_s = w_v/\rho_{Cu} = 5.28 \times 10^6$ J/kg, where $w_v = 4.7 \times 10^{10}$ J/m$^3$, $\rho_{Cu}$ is the density of copper, $w$ is the heat required to convert a unit volume of wire material in a metallic vapor, consisting of neutral atoms. In this connection this energy $\tilde{w}$ can be interpreted as the minimum energy density electro thermal destruction of wire material. $W_0$ is estimated as follows: for a source with storage capacitor—with use the integral the current action, calculated for the first quarter of the period; for a source with EMG—as the energy produced, with taking into account the efficiency of the transmission through the transformer. The total cross-sectional area of wires associated with integral current actions: $S_{sum} = \sqrt{I_d\rho_e/\tilde{w}}/\rho_{Cu}$, where $I_d = \int_0^\tau I(t)dt$ is the integral action, $\rho_e$ is resistivity. Initially, the current in the load for the first experiment was modeled numerically, with the thought that the wire breaks when the current at maximum value in the first quarter of the period. Next, input speed of critical energy density was estimated in adiabatic approximation $dW/dt = \dot{E}_c = \rho_e, W/m^3$, where $\rho_e$ was taken at a melting temperature $T = T_m$, $\dot{E}_c \approx 3.4 \times 10^{11}, \text{A/m}^2$ is critical current density for copper conductor, the parameters taken from [7, 11].

Time scale explosion of copper conductor was estimated from the law of conservation of momentum (the equations of motion given the equations of State, with the balance of the liquid and gas phases) so $\tau_c \approx r_0(\rho_c/p_c)^{1/2}$, where $r_0$ is the radius of the EEW, $\rho_c, p_c$—density and pressure at the critical point, for copper $\rho_c = 2.27 \times 10^3$ kg/m$^3$, $p_c = 9.04 \times 10^5$ bar, [12], for conductors with diameters 80–120 μm time scale is about 100 ns. Preliminary calculation gives the upper estimates. Therefore, two experiments was carried out for each source, the first experiment was starting point for the second. Consideration of the experimental results allows
us to refine the pulse sharpening and parameters to control the formation of the voltage pulse and the energy, inputted in the EEW.

3. Experimental and diagnostic base

Experimental model based on voltage pulse generator (VPG) is a laboratory stand generating EMP effect in a limited space $2 \times 2 \times 2$ m$^3$. Principal electrical schematic of the experimental model with the location of test equipment is shown in figure 1. VPG with 10 steps up the voltage was placed on a five-store frame. VPG with an initial voltage of 20 to 25 kV, the total capacitance $C = 1.2 \mu F$ was charged to $U = 200$–250 kV. Photo of experimental stand with VPG is shown in figure 2. In the foreground we see wires overhead line (OL) stretched on a frame located at the insulators and the voltage divider. The geometry of the overhead line in a grid allows to apply the approach of thin parallel plates for estimates of its inductance and capacitance. Wires EEW located at the end of the overhead line are the load on the circuit.

The experimental model based on EMG is the next laboratory stand generating EMP impact in a limited space of $2 \times 2 \times 4$ m$^3$. The source of pulsed current is explosive magnetic generator of spiral type with a current output to the load via a pulse transformer (PT) and transmission overhead line (OL). Direct and inverse OL branches are common to both models and locate on the insulators supports. Electro explosion breakers (EEW) are at the end of the OL. Principal electrical schematic with test equipment are shown in figure 3. Photo of the experimental model is shown in figure 4. Photo of EMG assembly before the experiment is in figure 5. Protective chamber for EMG during the experiment is in figure 6. The initial energy source for powering the EMG had capacity of 90 $\mu F$ and charged to 18 kV, so initial energy was about 15 kJ. Overhead inductance was also 5.5 $\mu H$, similar to the previous model. EMG has an outer diameter of 89 mm, an inner of 75 mm, polyethylene insert was 8.5 mm, and armature (inner copper tube) was filled with bulk explosives with weight of 2.17 kg. The transformer primary winding inductance was 0.14 $\mu H$, the secondary one is 14.5 $\mu H$, the coupling coefficient of 0.96, the transformation ratio of about 10. The EMG initial inductance was 21.9 $\mu H$.

Diagnostic tools with high-level of electromagnetic effects were additionally protected. Registrations were placed into metal boxes; all conductors to transfer useful signals if possible would be replaced with fiber optic communication lines. And all the control and test equipment was delivered in separate room. Electrical supply for initial energy was produced from a stand-alone generator by gasoline powered without electronic control. Computers and cameras are powered from the initial energy independent power with voltage stabilization. Overhead line outlets, as well as the used sources were grounded. The registrations which were used in experiments were test equipment, including Rogowski coils, voltage dividers and oscilloscopes. The results of the measurements obtained for each experimental model are shown below. Rogowski coils were used for registration directly derived currents and used without integrators. Currents were computed by integrating data with taking into account the sensitivity of each coil. Connection of oil filled high voltage pulse voltage divider shown in figure 3, dividing ratio 1 : 220000. The divider is designed for maximum amplitude of voltage up to 1000 kV.

For models with EMG we were measured: the derivatives of currents of EMG powering, in the transformer primary circuit and in the secondary circuit—the load (through the EEW). The results of measurements transmitted to the control room to the oscilloscopes also were duplicated by special devices designed for registration of local values of lightning currents. These devices have increased noise immunity, since their work is carried out completely autonomously and, moreover, they were placed in a solid metal housing. These devices represented the single-channel digital oscilloscopes which start record with the launch of the incoming signal.
Figure 1. Principal electrical schematic of experimental model based on VPG with measuring of current (with Rogowski coil, RC) and voltage (with divider, RD). Where: Ro—charging resistors; C—stage capacitance; F1–FN—spark gaps; Uc—initial voltage; L—OL inductance.

Figure 2. Photo of the experimental model with voltage pulse generator.
Figure 3. Principal electrical schematic based on EMG with measuring of current (with Rogowski coil, RC) and voltage (with voltage divider RD, and current transformer, CT); $L_{EMG}$—EMG inductance; $R_1$—primary resistance; $L_{1T}, L_{2T}$—inductance of primary and secondary circuit of pulse transformer; $L_{OL}, C_{OL}$—inductance and capacitance of OL. Where: 1—capacitor bank; 2—undermining; 3—explosion chamber; 4—armature with explosives; 5—pulse transformer; 6—overhead line; 7—electro-explosive wires; 8—voltage divider.

Figure 4. General view of an experimental model with EMG.

Figure 5. EMG assembly before install into explosive chamber.

Figure 6. EMG into explosive chamber with pulse transformer outside.
4. The results of the research of model with voltage pulse generator

Getting the model with high voltage pulse amplitude and short front is determined by the parameters of EEW. The length of the copper EEW was determined, on the one hand, the geometry of the high-voltage line of transmission, on the other—were estimated by the criterion of relationship breakdown voltage to the input speed energy. Criteria for similarity of the electrical characteristics of the wires explosion during the arc give the necessary lower boundary. The evaluations were carried out in accordance with the dependence in [2]. Thus, the length of the EEW was one meter. In the first experiment the energy from VPG was about 30 kJ. The conductors 120 $\mu$m in diameter were used in the number of 5 pieces. The weight of exploded conductors was 0.5 g. Initial conductors resistance was 300 m$\Omega$. VPG was charged to a voltage 232 kV. It is estimated that when the circuit inductance of about 11 nH, the maximum current should be about 70 kA, but EEW explosion occurred when the current has reached about 30 kA.

Values of pulse currents and voltages obtained in the experiment are shown in figure 7.

Maximum voltage rises to almost 800 kV due to rapid growth of resistance. The magnitude of the overvoltage was at 3.45. Estimation of the resistance growth rate gives a value of about 0.15 $\Omega$/ns, that is consistent with the experimental tables in [13]. The inputted energy amounted to about 5 kJ (specific inputted energy was about $\tilde{W}_0$ was about 10 kJ/g, the energy of sublimation of copper was 5.28 kJ/g, ratio $\tilde{W}_0/\tilde{w} \approx 2$), current density in the conductor reaches value of $4.7 \times 10^{11}$ A/m$^2$. Because the maximum current is less than the calculated value, it was decided to increase the number of wires in order to process the copper phase transformation began later. At the same time, the allowable value $\tilde{W}_0/\tilde{w}$ on the main criteria did not extend beyond.

In the second experiment, all other equal conditions the number of wires has been increased to 10 pieces. Weight of exploded wires amounted to about one gram. Initial resistance of wires was about 130 m$\Omega$. Measured pulse currents and voltages are shown in figure 8. EEW explosion occurred at current of 55 kA, almost twice as high previous, but the amplitude of the voltage was 575 kV, lower than the previous case. Therefore, the energy inputted in the EEW $\tilde{W}_0$ has increased only 7 kJ. Specific energy was while about 7 kJ/g, ratio $\tilde{W}_0/\tilde{w} \approx 1.4$. Estimation of the resistance growth rate gives a value of about 0.20 $\Omega$/ns, the current density in the conductor

![Figure 7. Current and voltage EEW in the first experiment with VPG.](image-url)
reaches around the value $4.5 \times 10^{11}$ A/m$^2$. Thus, we can assume that a value of the specific energy put in EEW affects to the amplitude greater than the total energy.

The maximum electric field strength in the experiments was approximately 800 kV/m in the interval of 1 m; the front of voltage pulse was about 100 ns. An estimate of changes of the magnetic induction was made by $\frac{\partial B}{\partial t} = \mu_0 N/(2\pi r_0) \frac{\partial I}{\partial t}$, in the approximation of single—turn coil ($N = 1$), where $r_0$—half the distance between the branches of the overhead line. For maximum derivative of the current corresponding to the break of EEW and power surges, we have $\frac{\partial B}{\partial t} = -0.2$ T/$\mu$s.

5. The results of the research of model with explosive magnetic generator

25 pieces of conductors with a diameter of 120 mm were used in the first experiment with current source—EMG. The total cross-sectional area is $28 \times 10^{-8}$ m$^2$. The total mass of all wires amounted to about 2.5 g. Number of wires defines the requirements to achieve the value of integral current action needed for the explosion wires at the stage of the current growth in the load. Results of experiments in the form of the measured pulse values of currents and voltages are presented in figure 8. Current power of EMG was about 57 kA. The break in the current graphics on 193 $\mu$m corresponds to explode EEW, and a further increase of the current associates with the EEW transition into the high plasma state. Voltage jump in the explosion EEW occurs during the current rise in the load, as planned, as is evident from the figure 8. The load current has two peaks, and the pause mode does not occur. The maximum current value is 127 kA. The voltage in the explosion was about 120 kV. Peak of voltage is approximately 1 $\mu$s from the first peak of current and indicates the beginning of an explosion. Estimates of the current density in the explosion were given the order value $10^{11}$ A/m$^2$. The growth rate of resistance was about 5 $\Omega/\mu$s. The energy, inputted in wires to 193 $\mu$m at the explosion, was approximately 12.5 kJ. Inputted specific energy of 12.5/2.4 \approx 5.2$ kJ/g, it is approximately equal to the sublimation specific energy of copper.

The experiment shows that this scheme can achieve higher voltages, if you go up the current curve closer to its second maximum value, as shown in figure 9. Therefore, the following experiment made a start by the characteristics obtained. 96 pieces of copper wires with
Figure 9. Current and voltage EEW in the first experiment with EMG.

Figure 10. Current and voltage EEW in the second experiment with EMG.

diameter of 80 mm each was used in the second experiment. The total cross-sectional area was $48 \times 10^{-8}$ m$^2$. The total mass of all wires amounted to about 4.3 g. The initial charging voltage was selected the same as in the previous experiment $\approx 18$ kV, which roughly corresponds to the initial energy of about 15 kJ.

Explosion EEW is illustrated in the graph a splash of current and the corresponding voltage peak in figure 10. Voltage jump occurs at the stage of growth of the current in the load close to the maximum current value. The voltage increases sharply to 550 kW for about 92 µm, figure 10. The maximum current value is about 70 kA. Voltage surge occurs in about 1 µs after the current surge in. Voltage pulse is within 200 ns, which corresponds to the limit of resolution
of measuring instrument. Then, for about 100 µs, EEW becomes in conductive plasma state of matter. Estimates of the current density value in the explosion were given near $3 \times 10^{11}$ A/m². Growth rate of resistance was about 16 Ω/µs. The energy, inputted at the explosion in wires to 92 µm, was about 60 kJ. Specific energy of 60/4.3 ≈ 14 kJ/g, approximately in 2.7 times more than specific energy of copper sublimation. Estimates of the maximum electric field strength in the experiments appearing in the gap between the branches of the overhead line (1 m), give the value of 550 kV/m. Front voltage is about 200 ns. It is known that the amplitude of the voltage 1.2 MW to about 200 ns front was registered in EEW break in the assembly for sources with EMG outside the laboratory [14]. This corresponded to the electric field of about 100 kV/m. Estimate of the magnetic induction variation that occurs in the gap around EEW, carried out as in the previous case of Ampere law in the approximation of single-turn coil ($N = 1$), then $\frac{\partial B}{\partial t} = \mu_0 N/(2\pi r_0)\frac{\partial I}{\partial t}$, where $r_0$ is the half of the gap between branches. Maximum of current derivative after breaking EEW was about 78 kA/µs, which gives the value $\frac{\partial B}{\partial t} = -0.124$ T/µs.

6. Conclusion

In experiments, with models of high-power generators on the basis of current pulses capacitive storage devices and explosive magnetic generators, the electromagnetic pulsed impact has been confirmed on experimental stands with electro-exploded wires. Voltage pulses with front of a few hundred nanoseconds have been obtained at the end of the forming line. The value of electric field strength achieved 800 kV/m. The growth rate of the magnetic field strength reached 0.2 T/µs. To continue research in this area EMP impact, specific energy input to the copper wires, $W_0/m$, can be increased up to 20 kJ/g [9]. To solve this problem stand should be improved in terms of increased noise immunity of diagnostic equipment. In particular, we need to go to stand-alone meter which worked well in the experiments; however, the temporal resolution of these devices must be increased.

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