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Analysis of lightning current distribution in lightning protection system and connected installation

***Abstract**. The aim of this paper was to analyze lightning current distribution in a typical lightning protection system (LPS) and connected supplying electrical installation. Some preliminary tests done in 2012 for the real scale test house model equipped with the LPS and connected to the 15kV/400V supplying transformer station showed that the most of the current flew through the transformer grounding. Moreover, shapes of the current wave-forms in the LPS grounding rods were different from the surge, and strongly dependent of the transformer grounding characteristics. In order to make precise analysis a simple model of the LPS was prepared at the open test site. The model was a frame consisted of rectangular air terminals and two grounding rods. Transformer circuit was connected to the one side of the frame near the ground surface. The lightning stroke current was injected to the frame with application of 10/15 µs stroke generator of energy about 10 kJ. Measurement was done for several different configurations of the LPS, and for current amplitudes varied from 100 A up to 3 kA. The results indicated variation regarding both, the amplitude and the shape of the waveforms. The most significant changes were due to trans-former grounding influence. The rising time of the waveforms changed highly when the transformer was connected to the LPS. In correspondence to the current measurement total resistance was verified. The resistance was measured for several groundings individually and totally in respect to the generator surge location. Typical results were observed in this case. Further simulation was based on the evaluation of the generator current by the measured resistances in order to obtain theoretical currents in different points of the LPS. Direct comparison of measured and computed waveforms showed distinct character of the real circuit. Therefore, in order to improve current simulation accuracy the grounding system impedance should be considered rather than the pure resistance.*

***Streszczenie.** Celem artykułu była analiza rozpływu prądu piorunowego w urządzeniu piorunochronnym oraz połączonej instalacji zasilającej. Testy generatorowe wykonane w 2012 roku na modelu domu wyposażonego w instalację odgromową oraz podłączonego do transformatora 15kV/400V pokazały, że największa część prądu udarowego odpływała do uziemienia transformatora. Kształty przebiegów prądowych w różnych punktach instalacji różniły się, były również bardzo zależne od rezystancji uziemienia stacji transformatorowej. W celu dokonania precyzyjniejszej weryfikacji przygotowano uproszczony model instalacji odgromowej w postaci prostokątnej ramki złożonej z dwóch zwodów połączonych z uziomami pionowymi. Obwód transformatora był połączony do jednego z uziemień ramki. Kilka odrębnych konfiguracji całego systemu zostało zbadanych dla prądów w zakresie od 100 A do 3 kA. Rezultaty uwidoczniły silną zmienność kształtu oraz amplitudy przebiegów prądowych. Największy wpływ miała wartość rezystancji transformatora. Zweryfikowano również wartość rezystancji poszczególnych elementów indywidualnie oraz rezystancję zastępczą całego systemu. Otrzymano wyniki zgodne z obliczeniami symulacyjnymi. Na bazie rezystancji oraz prądu na wyjściu generatora obliczono prądy teoretyczne w instalacji. Bezpośrednie porównanie z wartościami rzeczywistymi uwidoczniło pewne różnice. W celu poprawy dokładności odwzorowania rozpływu prądów konieczna jest weryfikacja z uwzględnieniem impedancji systemu, a nie wyłącznie rezystancji. (**Analiza rozpływu prądów udarowych w urządzeniu piorunochronnym oraz połączonej instalacji**).*

Keywords: lightning protection system, stroke current, grounding system resistance
Słowa kluczowe: instalacja odgromowa, prąd udarowy, rezystancja uziemienia

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Introduction

Experimental investigations of distribution of currents in the lightning protective systems (LPS) of residential buildings were conducted in several countries in two last decades. University of Florida (UF) is the leading center of such investigations. Experiments on lightning currents in LPS, using the rocket-and-wire technique to trigger lightnings, were conducted at belonging to the UF the International Center for Lightning Research and Testing (ICLRT) in Camp Blanding, Florida. These experiments, mainly conducted in 2004 and 2005, gave a set of valuable results [1].

The lightning research group at Rzeszow University of Technology (RUT), in cooperation with the ICLRT, conducts from 2007 the experimental investigations of surge current distribution in LPS of small structures. The experiments at the RUT are aimed on examination the current waveforms in different parts of the circuit and the distribution of the injected surge current between the grounding system of the LPS, supplying line and electrical installation of the building [2, 3]. Our last investigations were conducted in new open-air laboratory for testing of lightning protective systems of small structures built on a terrain of about 5 ha in Huta Poreby, 50 km far from the RUT.

Among many valuable aspects of obtained results the dependences of distribution and shape of current surges on the dimensions and shapes of tested circuit and on the resistances of earthing system are especially interesting. In most cases the main elements of tested circuits are the earthed conductors of LPS heaving a shape of some kind of near-rectangular frame with dimensions in the range of several meters or a bit above ten meters connected to the underground cable line heaving the length of some tens of meters ended with earthing at the transformer substation. The resistance of this earthing is usually distinctly smaller than the resistances of individual earth electrodes of the LPS.

Basing on these statements, the lightning research group at the RUT decided to conduct experimental investigations of surge current distribution in special circuit composed of an earthed frame shaped conductor and underground cable line earthed at the remote end.

Experimental Setup

The investigations of surge currents were conducted in the circuit presented in Fig. 1. The frame part of the circuit was constructed using round galvanized steel wire with a diameter of 8 mm. It consists of ten meter long horizontal part and two vertical parts connected to vertical ground rods each having a diameter of 20 mm and a length of 1.5 m. This circuit part was connected to the PEN of 50 m long underground cable via the 3.2 m long insulated conductor. The cable PEN was connected at its remote end to the transformer substation grounding system composed of two horizontal parallel flat bars 8 m long placed in the soil at the depth of 60 cm (see Figs. 1 and 2). The tested circuit was equipped with three current shunts (Figs. 1 and 3). Two of them (A1 and A2) were connected between the ends of frame and vertical ground rods, while the third shunt (A3) was connected at the input of cable PEN.

Measurements of currents in the tested circuit were done using the test and measurement setup presented in Figs. 2 and 3. A generator of lightning current surges (9) was the main device of the test system. The main nominal parameters of the generator are: maximum storage energy 10 kJ, operating voltage 10 - 80 kV, maximum surge current 50 kA. Thanks to possibility of precise setting of operating voltage the generator can produce strictly repeatable current surges. The generator output terminal was connected, via insulated copper conductor (8) having cross-sectional area of 16 mm2, to the frame horizontal part (7).

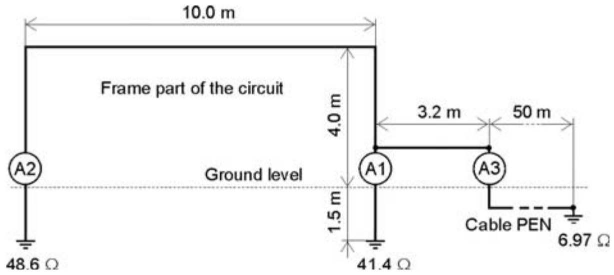

Fig. 1. The diagram of tested circuit with measuring points (A1, A2 and A3) of distributed surge current.

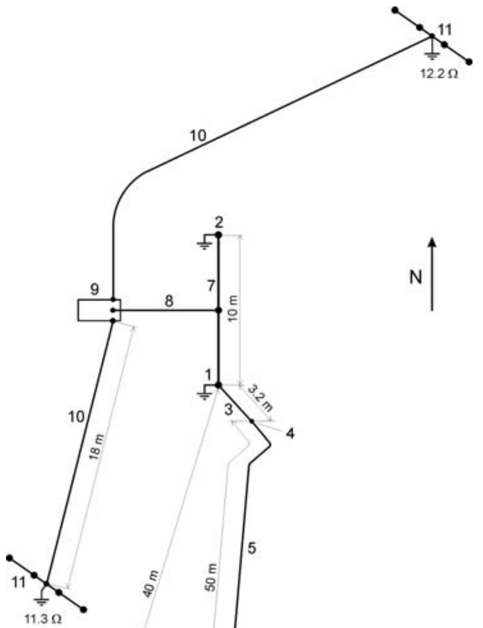

Fig. 2. Schematic diagram of experimental setup and test object: 1 and 2 - vertical grounding rods, 3 - insulated copper conductor, 4 - free standing cable joint, 5 - PEN conductor of underground cable, 6 - grounding system of transformer station, 7 - frame part of tested circuit, 8 - insulated copper conductor, 9 - current surge generator, 10 - return circuit insulated conductor, 11 - four interconnected grounding rods.

The functioning of the test setup can be easily explained by tracking the current distribution in the tested circuit. Injected surge current can flow in the frame horizontal part (7) in two directions and then in the vertical parts to the ground rods (1) and (2) and to the soil (see Figs. 2 and 3). In the case of the ground rod (1) a part of the current can flow in insulated conductor (3) connecting this ground rod with the cable PEN (5) at the free standing cable joint. This current can flow in PEN conductor of underground cable (5) and through the station grounding system (6) into soil.

The dc grounding resistances, depicted in Figs. 1 and 2, for each grounding location were measured using the fall-of-potential method [4]. Soil conductivity at the site where the test system was built has been measured using the four-probes Wenner method and its value was approximately 18.7·10-3 S/m. Injected current was measured at the generator output terminal (measuring device A0), while the distributed currents were measured at points labeled A1, A2 and A3 (see Fig. 3.)

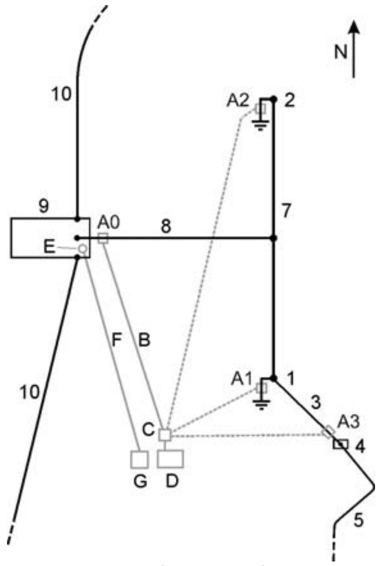

Fig. 3. Schematic diagram of a part of experimental setup with measurement system: 1 and 2 - vertical grounding rods, 3 - insulated copper conductor, 4 - free standing cable joint, 5 - PEN conductor of underground cable, 7 - frame part of tested circuit, 8 - insulated copper conductor, 9 - current surge generator, 10 - return circuit insulated conductor, A - current shunt, voltage divider, analogue-digital and electro-optical converters, B - optic waveguide, C - optoelectronic converter and memory buffer, D - laptop, E - optoelectronic converter, F - optic waveguide, G - digital controller of generator with electro-optic converter.

Entire current flowing in the soil can find its way back to the generator through two sets of vertical grounding rods (11) and two insulated conductors of the return circuit (10). To achieve possible uniform distribution of test current in the soil and possible low impedance on its way, eight grounding rods of the return circuit were located in considerable distances from the tested circuit.

An essential part of the experimental setup was the electro-optic measurement and registration system. This system was composed of three basic parts (see Fig. 3): a converter of measured quantity (A), transmission line (B), and meter (recorder) of measured quantity values (C and D). The converter (A) was built using four different devices: current shunt having a resistance of 10 mΩ, voltage divider, analogue-digital converter and electro-optic converter. Converted discrete instantaneous values of current in the form of light impulses were transmitted with optic waveguide (B) to measurement (registration) part of the system. This part consists of optoelectronic converter and memory buffer (C), and laptop (D).

The electro-optic measurement and registration system is characterized by: the range of input voltage values (from output of current shunt) from 0 to ±100 V, maximum sampling frequency of measured voltage 50 MS/s, frequency band of conversion and transmission from 0 to 20 MHz, output function in digital form readjusted to a laptop USB, and autonomous battery supply. All data transmitted with optic waveguide have digital form and are not susceptible to electromagnetic disturbances and weather conditions.

Measurements and registrations of current distributed in tested objects were possible with the use of one electro-optic measurement system, thanks to strict repeatable current surges produced by the generator. This repeatability is guaranteed on condition that the impedance of an object connected to the generator output terminal do not changes during successive measurements. Moving and connecting the parts A and B of the electro-optic system (see Fig. 3) successively to selected elements of the test object the registration of current distribution can be done for injected repeatable current surges.

Experimental Results and Discussion

Several measuring sessions were done at the open test site in Huta Poreby in 2012. Two of them strictly concerned mentioned configuration. Different modifications of the circuit from Fig. 1 were checked for generator impulses rising from 10 kV up to 50 kV. Only selected results were presented in the paper. Due to limitations of the measuring setup currents lower than 100 A were not recorded by the system. In this case currents were derived from the remaining waveforms. This situation was mainly for grounding rod currents A1 and A2. The sum of the currents, A1+A2, was computed by the generator and transformer current subtraction. For some waveforms an additional offset correction was needed. Three major configurations were arranged. The only difference was the depth of grounding rods R1 and R2 which influenced directly on the grounding resistance.

Measurement, regarding the configuration from Fig. 1, was done in order to check general distribution of the generator current in the model of LPS and supplying transformer circuit. The results for 30 kV and 40 kV from the generator were presented in Figs. 4 and 5. Currents observed in both cases were similar to those recorded previously for the real LPS installed at the test house. It confirmed that the frame was good representation of the real installation. Moreover, the measured resistances of the particular rods were close to those obtained for the test house model. Comparing amplitudes of currents the performance of this part of the LPS consisted of grounding rods was poor. Most of the surge current flew through the PEN wire of the isolated cable to the transformer grounding. The ratio of the transformer current and rods current was approximately 2.14 while theoretically, on the basis of measured resistances, it should be 3.21. This relatively high difference was because only resistance was taken into account. There is necessity to measure impedance parameters of groundings. In the future this kind of measurement is planned with application of MZ-407 manufactured at the Gdansk University of Technology, Poland [5]. Different impedance character of the particular elements of the system was observed for all recordings. Current peaks were reached at different moments of time. In case of grounding rods the rising times were short which correspond to the higher frequency components. On the other hand the content of lower frequency was greater for relatively low resistive transformer grounding. The reason was probably an influence of the inductance of the long cable connection between the LPS and transformer grounding. This is particularly important for the lighting surges where the content of higher frequency components might be significant. In case of the direct discharge into LPS, faster components dissipate in the protected area, while the rest of the lightning current flow to the supplying station. The flow of fast components to the ground might be dangerous for systems located in the building, even not physically connected to the electrical installation. The electromagnetic fields and capacitive coupling might be the source of overvoltages induced in the electrical appliances located near the air terminals.

Comparing Figs. 4 and 5, currents are almost the same regarding shape and amplitude ratio between waveforms. The impedance character of particular elements remained un-changed during the tests. No nonlinearities were observed in this case. The highest current amplitude was about 3 kA which is not enough to initiate ground discharges. Further tests with generators of greater energies and for circuits of lower impedance are planned in order to check the influence of this phenomena on lightning current distribution.

The following analysis was to check influence of different configurations of the frame on current distribution. The frame was measured for two arrangements of grounding rods R1 (A1) and R2 (A2) (Fig. 1). The depth of R2 was changing in order to simulate high, and close grounding resistance comparing to the R1. It is a continuation of previous research in Camp Blanding, Florida [2] where the similar system was under influence of triggered lightning strokes. The same configuration was developed at the open test site near the campus of Rzeszow University of Technology in 2007 [6]. The intention was to verify previous research obtained with application of the oscilloscope and BNC wired connections. During the research done in Camp Blanding and Rzeszow, for some configurations of LPS, the current amplitude observed in grounding rods was higher than the surge. Authors suggested that the reason might be the inductance of the frame composed of air terminals, grounding rods and soil. The difference of the grounding resistance between rods and supplying circuit grounding forced the current to flow mainly to the transformer through only one side of the air terminal. The asymmetrical distribution of the current at the frame gave resultant inductance stream through the frame surface. Self-inductance was the reason of the additional current induced in the frame. The second possibility of the current amplitude increase, suggested on the basis of the re-search done at the campus of Rzeszow University of Technology, was influence of measuring setup. Especially BNC connections between the shunt and oscilloscope were taken into account. In the paper both hypotheses were under verification. The most recent results were shown in Fig. 6. Firstly, R2 was at depth of only 15 cm. The measured grounding resistance was 717 Ω, respectively.

The relatively high grounding resistance R2 was selected to force current to flow to the transformer grounding. Unfortunately, the effect of the amplitude increase was not observed in the case. The ratio between R2 and transformer grounding resistance was oversized. The waveforms for R1 and R2 were not recorded due to sensitivity of the measuring setup. Only the sum of currents to grounding rods was computed from the generator and transformer waveform. The most of the current flew through two sides of the frame and dissipated in the transformer grounding. The asymmetry of the current was strong but the mentioned effect was not appeared. The resistance in the frame loop was too high which prevented induced current to flow. The only possibility was to decrease the resistance by deeper position of grounding rods.

In the second case R2 was at full depth of 1.5 m, and only 173 Ω was measured for this configuration. However, the result was similar. The ratio of the transformer and frame grounding resistances was still too high to observe induced current. Moreover, currents were too low to exceed measuring system trigger level. There was no option for further resistance decrease with application of the single grounding rod.

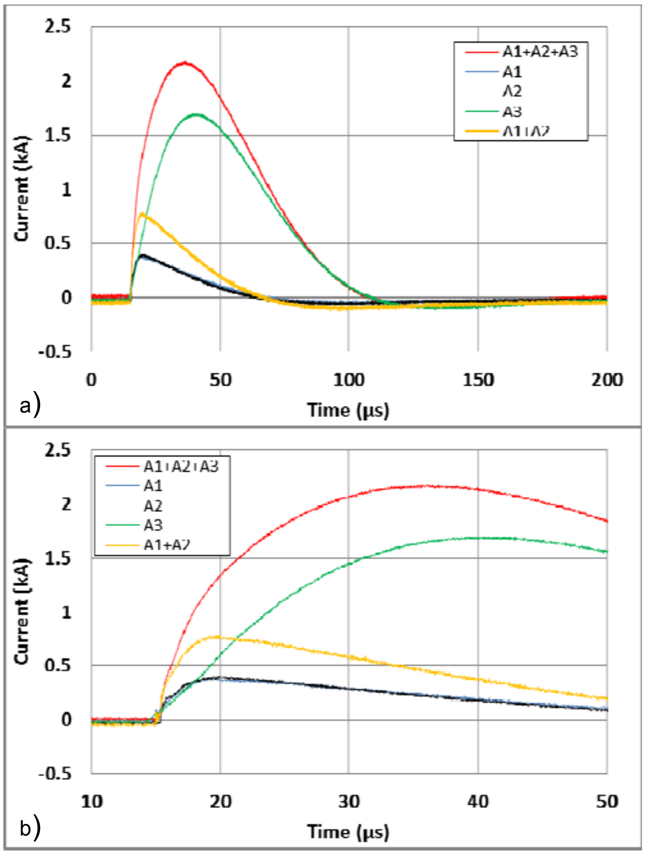

Fig. 4. Distribution of the current in the frame and supplying installation (Fig. 1) for 30 kV from the generator. Notice that in case of Figs. 4 to 7 the only difference between a) and b) is time scale.

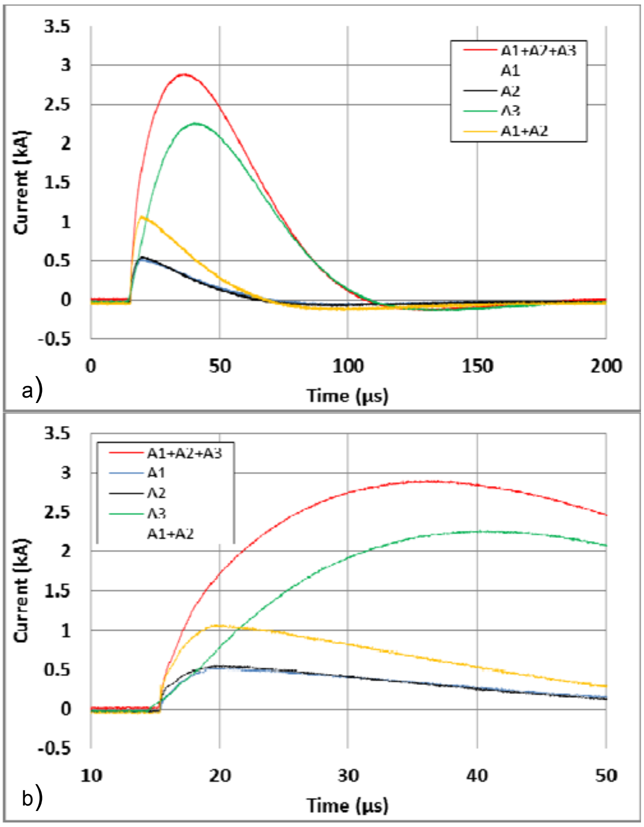

Fig. 5. Distribution of the current for the same configuration as in Fig. 4. for 40 kV from generator.

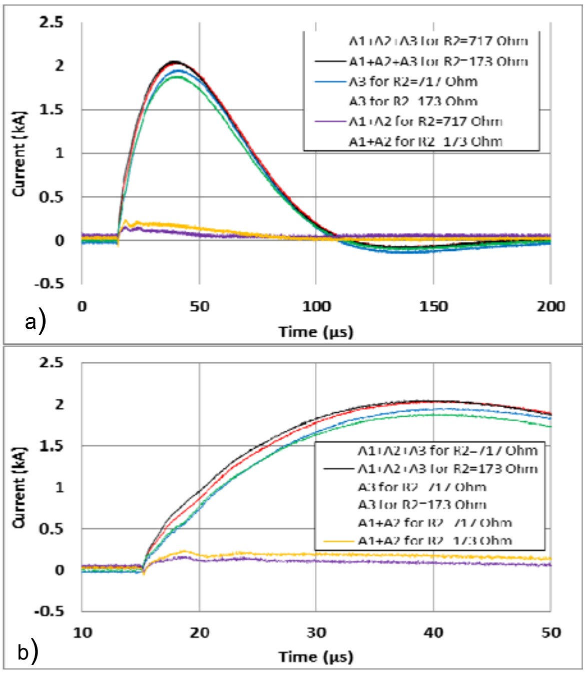

Fig. 6. Comparison of selected currents for different depths of R2 grounding rod. In the first configuration R1=160 Ω; R2=717 Ω; Rtrafo=6.28 Ω. For the second arrangement where R2 was buried deeper R1=164 Ω; R2=173 Ω; Rtrafo= 6.28 Ω.

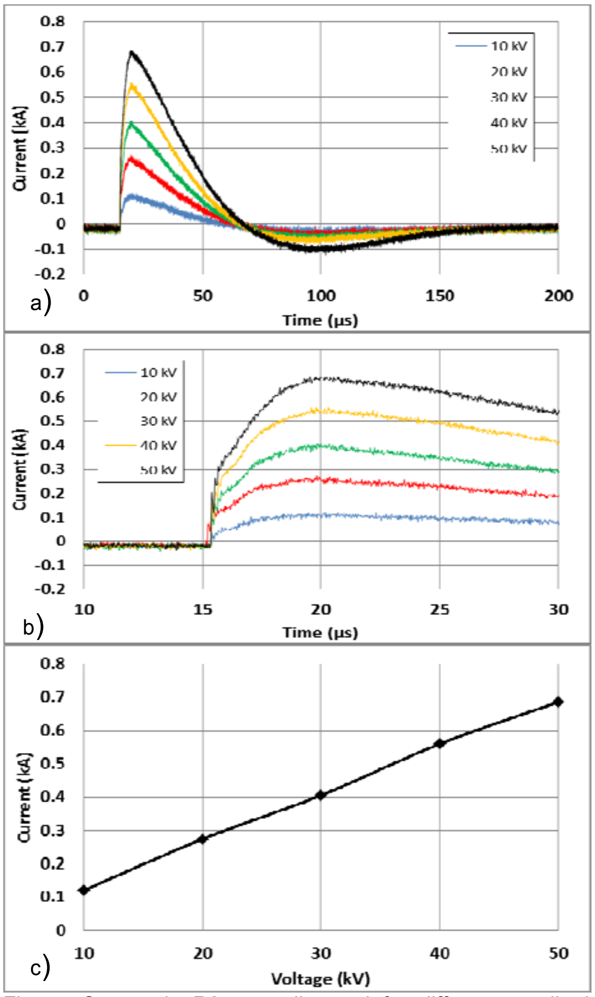

Fig. 7. Current in R2 grounding rod for different amplitudes of surges from the generator – a,b). Influence of the surge generator voltage on the maximum of the current in R2 grounding – c). Notice: system configuration and grounding resistances of frame as for Fig. 4.

Therefore, the following analysis was based on the results presented in Figs. 4 and 5. For this configuration resistances of particular rods were about 45 Ω which is four times lower than for the frame from Fig. 6. In order to make comparison with currents obtained for the frame, in Figs. 4 and 5 an additional type of the waveform, A1+A2, was introduced. It gave information about current in the frame loop. The ratio of the sum A1+A2 and generator current was about 30 % and was independent of the surge amplitude. The same ratio was only 10 % for results presented in Fig. 6. The shape of waveforms gave more information about the character of phenomena observed in the LPS. In each case the maximum of the grounding rod current occurred during the rise of the generator current. For only one shape of the generator impulse, it is difficult to state that the waveforms A1 and A2 are dependent on the surge derivative. Tests with application of different impulses are needed to make reliable analysis and verify physical relationships.

An additional analysis of the influence of the voltage applied from the generator was done. The result was presented in Fig. 7. Except the amplitude, an interesting conclusion from Fig. 7 was that the shapes of particular waveforms were similar each other. The peaks were reached directly at the same time independently of the generator voltage amplitude. The analysis proved that the amplitude of the current in the grounding rod is proportional to the surge amplitude.

The second of mentioned hypotheses that increase of the current amplitude might be the result of measuring setup influence was proved indirectly by recordings with application of fibre-optic links presented in the paper. Comparing the results of previous research [2,6] with recent registrations there was strong difference at the rising slope of current waveforms. More reliable results from the fibre-optic system were smooth and there was no effect of capacitive coupling, as in case of BNC wires.

Conclusion

Experimental investigations of distribution of currents in the lightning protective systems (LPS) of residential buildings were conducted in several countries in two last decades. University of Florida (UF) is the leading center of such investigations. Experimental tests done at the open test site and laboratories of the Rzeszow of Technology, Poland, were a continuation of the research at the UF the International Center for Lightning Research and Testing (ICLRT) in Camp Blanding.

Some of the hypotheses regarding the current distribution in LPS were verified in the paper. First of all, the typical distribution of the current corresponding to the lightning phenomena was checked practically on real scale objects. The current was measured with application of the fibre-optic system. It ensured high level of reliability. Waveforms recorded with application of the system were smooth and not disturbed on their rising slopes.

In order to analyze effect of the current amplitude increase in one of LPS groundings, the simple LPS was arranged in form of the frame and connected supplying circuit. The resistance of the transformer grounding was low comparing to the rest of frame groundings. Therefore, the most of the current dissipate in the transformer circuit. The performance of the LPS was poor mainly due to relatively high grounding resistance of the frame. The same relationship was observed in full configuration of LPS installed to protect test house. It was difficult to observe the effect of the amplitude increase because of the high resistance of the frame loop. Further tests are planned for different configurations of the LPS, especially for lower resistance of the grounding rods and for other sizes of the frame. The surge type had no influence on the ratio of recorded currents. The waveforms were proportional to the generator voltage. No nonlinearities were observed in the soil in this case. Other generators will be used in the future to verify the current distribution for various shapes of the surge in order to simulate different components of the lightning stroke.

Acknowledgment

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