EXPERIMENTAL ANALYSIS OF IMPULSE CHARACTERISTICS OF GROUNDING GRIDS WITH AND WITHOUT RODS

تحليل معملي للخواص النبضية لشبكات التأريض مع وجود وعدم وجود قضبان

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خلاصة

تتعرض المحطات الكهربائية ومعداتها للارتفاع اللحظي في الجهد الكهربي الناتج من حدوث الصواعق الكهربية (جهود دفعية) أو التيارات العالية نتيجة حدوث تيار القصر الأرضي وبناء عليه فإن معاوقة شبكات التأريض لها يجب أن يتم حسابها بدقة. وتعتمد خصائص الشبكات الأرضية في حالة وجود جهود دفعية على كل من: خواص التربة ومكونات شبكات التأريض وما إذا كانت مضاف إليها قضبان من عدمه وكذلك على شكل موجة الجهد الدفعي ولحظة تفريغ الشحنة العالية الناتجة عن الصواعق.

يقدم هذا البحث دراسة معملية تفصيلية لحساب المعاوقة الأرضية لشبكات التأريض مع وجود قضبان بها عند تعرضها للجهود الدفعية اللحظية، وقد أجريت الدراسة على ثلاثة نماذج معملية لتحاكى أنواعاً مختلفة من التربة ذات طبقة واحدة أو طبقتين أو ثلاث طبقات مختلفة.

Abstract

Impulse characteristics of grounding systems have a great influence on proper evaluation of substation equipment stresses from lightning overvoltages, protection and design points of view. The grounding grid impulse characteristics depend on: grid parameters and soil characteristics as well as on the impulse current shape, magnitude and discharge point. The addition of driven rods to the grid has an action on grounding grid impulse characteristics.

This paper presents an experimental study for determining the impedance of grounding grid with and without driven rods. Tests are conducted on three scale models to simulate single-, double- and triple-layer soils. Also, the impedance of grounding grid calculated mathematically from the generalized equations which matched the impedance, voltage and current wave shapes. The values of grounding grid impedances determined experimentally and mathematically are compared. The comparison was closed together and satisfied.

1. Introduction

When lightning strikes an electric substation, large currents flow in substation and equipment structures before dissipating in the soil through the grounding system. The electromagnetic fields generated by such lightning surges will result in large currents and voltages, which may cause damage to the equipment, and may be dangerous to the personnels working nearby. Moreover, modern electronic circuits generally have weak signal levels and are sensitive to various kinds of electromagnetic disturbances. The undesirable electromagnetic fields induced by the lightning current may

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cause measurement error or result in damage to the electronic circuitry [1].

Protection from induced strokes is conferred by the same means as for direct strokes. Lightning can cause damage to structures by direct stroke and to electric equipment by surges coming in over exposed power lines. Surges may be the result of direct strokes to the line at some distance away, or they may be electrostatically induced voltages. Damage due to direct stroke can be minimized by providing a direct path of low resistance to earth. It is not possible to positively protect a structure against damage from direct stroke, except by completely enclosing it with metal. Lightning cannot be prevented; it can only be intercepted or diverted to a path that will, if well designed and constructed, not result in damage. Even this means is not positive, providing only 99.5-99.9% protection. Complete protection can be provided only by enclosing the object in a complete metal (or metal mesh) encapsulation [2].

The fault of high current flow to substation grounding may be the happening of lightning or short-circuit to grounding system. It causes potential difference which initiates electrical current paths through human body. If the current is higher than tolerable human, the result may shock him to death. Good design of substation grounding system is achieved if the grounding system resistance is low [3].

The impulse characteristics of grounding grid depend on grounding grid parameters and soil characteristics as well as on the impulse current shape, magnitude and discharge point. Comprehensive mathematical models have been derived for the transient grounding system analysis in the past [4]; however, there are only a few reports on experimental data. Such data are important for the verification and further enhancement of available analytical models. The methods of physical modeling are based on the investigation of the grounding grid in electrolytic tank. A series of experimental investigations of grounding grid (16-mesh) and grounding grid (16-mesh with 25 rods) configuration have been performed for a single-, double- and triple-layer. The impulse characteristics have been determined in terms of discharge points and injected current shapes. The presented graphs can be used to verify and improve analytical models applied in substation grounding system and lightning protection design [4]-[5].

Most previous studies presented about this topic are applied to single- or double-layer soils' structure [4]. In some of the previous work, e.g. [5], the water was used to represent the top layer and ager for the bottom layer. The main disadvantage of this model is that the resistivity of the media could not be closely controlled and maintained for a long time. In most previous studies the scale models were constructed from galvanized iron, and supplied by 220 volt AC-supply using a variac. Meanwhile, impulse characteristics of grounding grid were not analyzed in details [4].

In this paper the scale models are constructed from aluminum (non-magnetic material) which is more suitable for high frequency applications than the galvanized iron. A 10 kV impulse wave is used. A new suggested comparison method which provides main features for the influence of adding driven rods to the grounding grids by using scale models (single-, double- and triple-layer for 16-mesh grounding grid and grounding grid 16-mesh with 25 rods) is experimentally analyzed. Suggestion of new generalized equations matching to the curves of the impulse voltages and currents for the last mentioned models are also introduced, consequently the impedance of the grounding grid are determined.

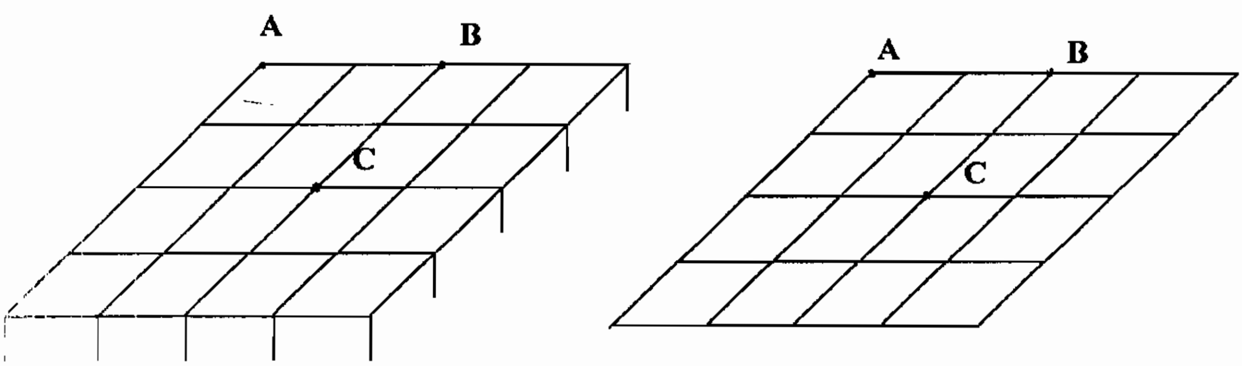
2. Measuring Scheme and Test Procedure

In order to determine the impulse characteristics of the grounding grid in real conditions considering the voltage and current wave shapes as function of time for single-, double- and triple-layers, series of experiments were carried out using an impulse generator [6]. The used impulse generators (1.2 / 50 μs) are designed to simulate lightning and switching impulses, as required by ANSI (American National Standard Institute), IEEE (Institute of Electrical And Electronics Engineer) and IEC (International Electro-technical Commission) requirements. The impulse grounding impedance of grounding electrodes is the impedance value measured between the point where the impulse current is injected into the grounding system and another electrode of zero grounding resistance in the ground at infinite spacing [7]. The impulse impedance has highest value at the beginning of the ascent of the wave front and diminishes finally to the steady state grounding resistance [8]. The impulse generators are comprised of a control, triggering unit, impulse generator stack and a dc charging supply. Normally a voltage divider, measurement system and other accessories are added to the basic system. Experimental investigation has been made at an impulse voltage of 10 kV. The voltage measurement of the grounding grid potential is carried out by using an oscilloscope [9].

The soil characteristics were determined by measuring TDS (total dissolved salt). Three models are used during the experiments. A 16-mesh grounding grid and a 16-mesh grounding grid with 25 driven rods (rod length = 3 Cm) were made of copper with diameter 1 mm. Three test charge points are considered A, B and C as shown in the Fig.1. The impulse impedances were determined using the following expression: $Z = V/I$

where: V = maximum voltage at discharge point.

I = injected current magnitude at the time instant when V has been reached.



a) 16-Mesh grid with 25 driven rods **b) 16-Mesh grid**

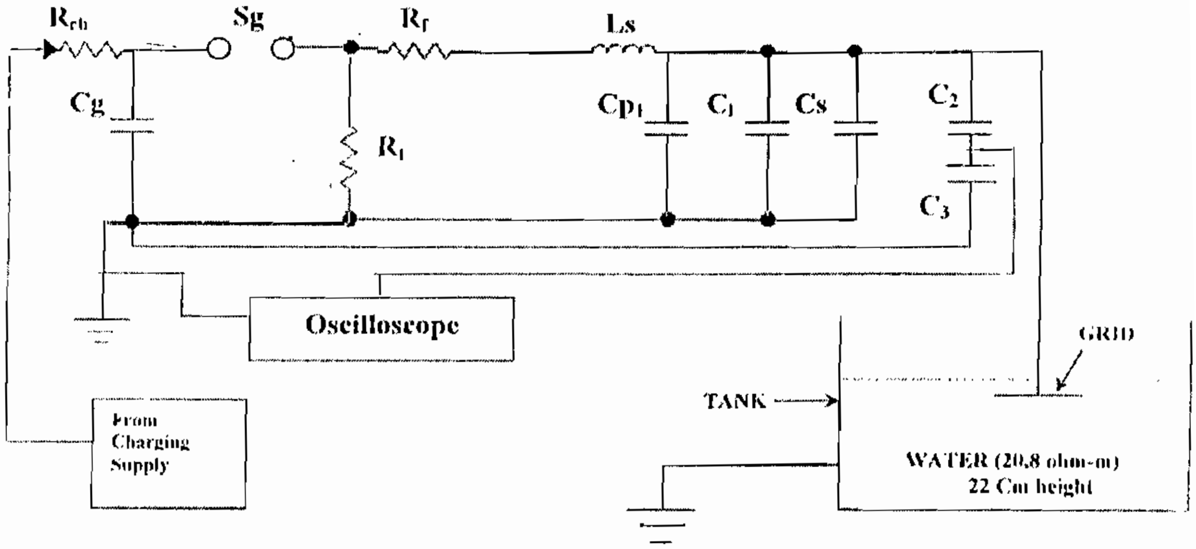
Fig.1 Grid types and discharge points (A, B and C)

3. Experimental Results and Discussions

3-1 Single-Layer Model

To represent a single layer soil, an aluminum tank is constructed with dimensions of 95 cm X 95 cm X 70 cm. The tank is filled with water with a resistivity 20.8 Ω-m and to a height of 22 cm. Fig. 2, illustrates the impulse test circuit for the studied model.

Five series were performed (V_A, I_A), (V_B, I_A), (V_C, I_A), (V_B, I_B), (V_C, I_B), so that five cases were studied and analyzed.



- Sg is the spark gap in each stage.
- Cg is the capacitance of each stage of the impulse generator (200 nF).
- Ls is the inductance per stage impulse generator 4.4 μH.
- R_t is the tail resistance per stage 333.33 Ω.
- R_f is the front resistance per stage 15.8 Ω.
- C_l is the capacitance value of the test object in nF.
- C_{pl} is the capacitance value of the front or pre-load capacitor in nF.
- C_s is the stray capacitance of the hv circuit in nF.
- C_2 is the capacitance of the voltage divider 1482 nF.
- C_3 is the capacitance of the voltage divider 204 nF.
- R_{ch} is the value of the charging resistance per stage 17 kΩ.
- N is the number of stages of the impulse generator.
- The total capacitive load on the generator is the sum of the individual loads:

$$C_t = C_l + Cp_l + C_2 + C_s = 39.5 \text{ nF}$$

Fig. 2 Impulse test circuit for single-layer model (16 mesh grid with and without 25 driven rods)

Case no. 1 In this case the measured quantities are the impulse voltage at the discharge point A of the grounding grid configuration and current wave-shapes at the same point (VA, IA). The tests were applied for 16-mesh grid and 16-mesh grid with 25 driven rods. The results obtained in this case are illustrated by Figs. 3 and 4.

The results show that both the impulse voltage amplitude and the voltage front rise time decrease by 8.16% and 11.36% respectively after using driven rods. Whereas, the impulse current amplitude increases by 12.32% and its front rise time decreases by 37.42%. The impulse impedance decreases by 19.48%. The other four case studies give similar results and the complete results of the five cases studied are shown in Table 1. The obtained results are in agreement with the theoretical and experimental ones attained by other published papers [10]. The value of impulse impedance decreases as the peak value of the current increases, tending towards a limiting value that depends on the structure and resistivity thereof of the soil.

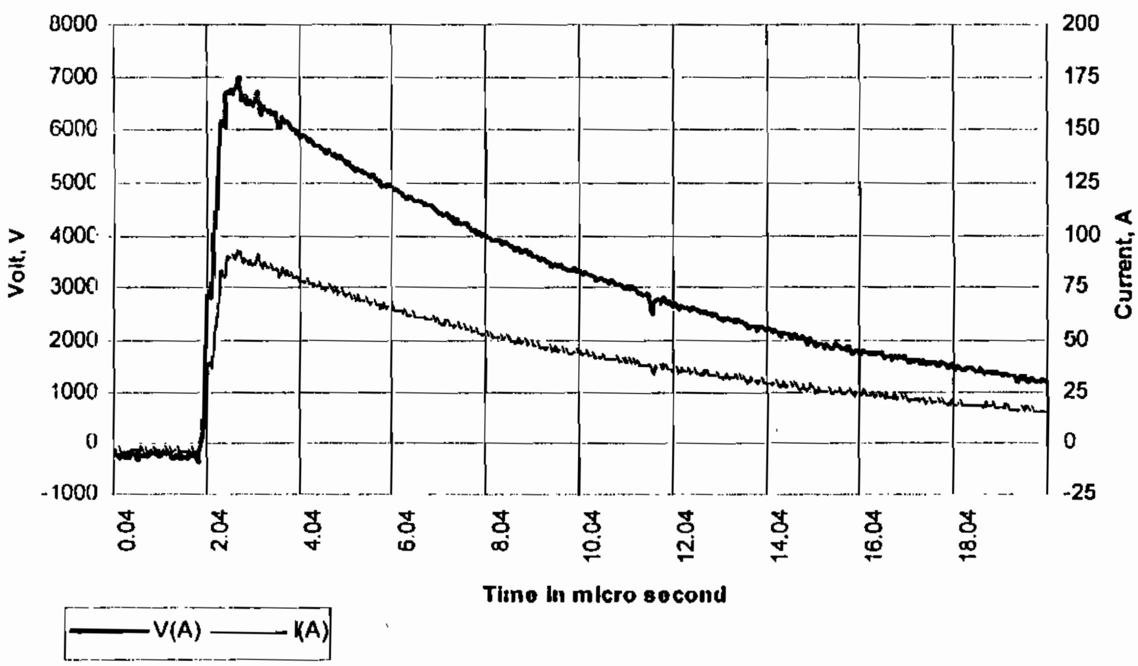


Fig 3 V_A and I_A at discharge point A for single-layer model (16 mesh grid)

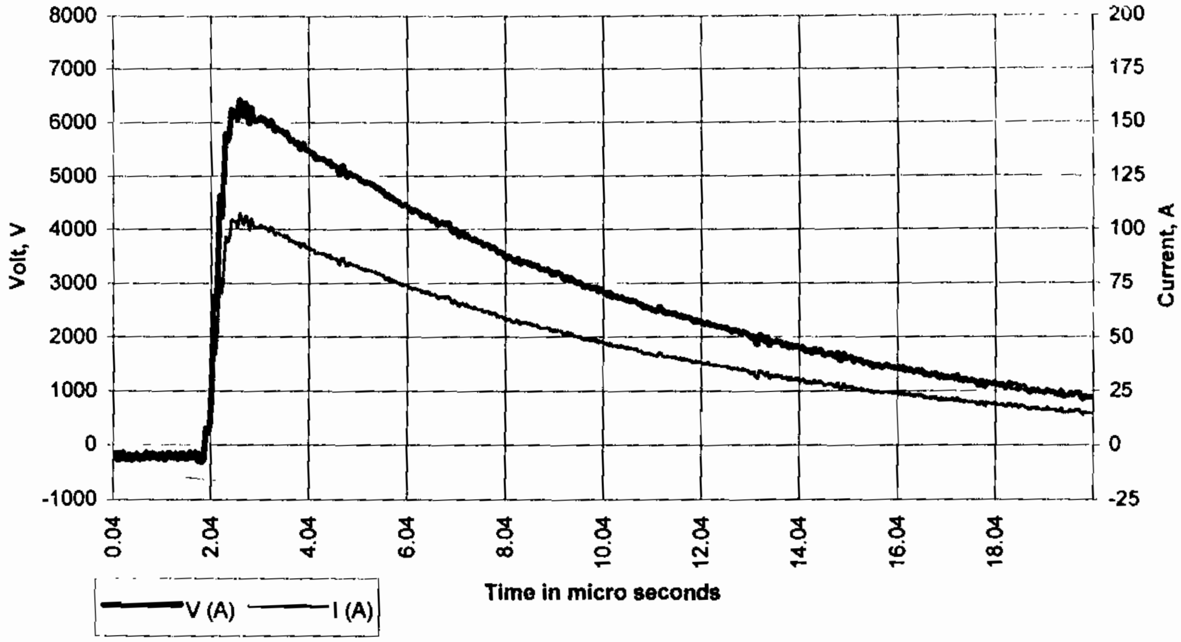


Fig 4 V_A and I_A at discharge point A for single-layer model (16 mesh grid with 25 driven rods)

Table 1 Single layer experimental results

Case Study No.	Discharge Point	Measuring Quantities	16-Mesh grid without rods					16-Mesh grid with 25 rods				
			Shape Parameters				Z (Ω)	Shape Parameters				Z (Ω)
			Voltage		Current			Voltage		Current		
			V	T1/T2 (μs)	I	T1/T2 (μs)		V	T1/T2 (μs)	I	T1/T2 (μs)	
1	A	V_A, I_A	7000	0.66/7.33	93.33	.668/7.15	0.7500	6420	.585/6.78	107.00	.418/7.18	0.6000
2	A	V_B, I_A	6840	0.96/7.513	90.13	.668/7.26	0.7589	6480	.835/6.70	105.00	.376/6.813	0.6171
3	A	V_C, I_A	6940	0.585/7.13	91.11	.501/7.45	0.7617	6340	.484/6.74	104.33	.418/6.63	0.6077
4	B	V_B, I_B	6840	0.543/7.163	90.59	.501/7.03	0.7550	6480	.585/7.125	107.75	.651/7.095	0.6013
5	B	V_C, I_B	6940	0.501/7.3	89.90	.501/7.58	0.7719	6340	.418/6.73	102.67	.551/7.125	0.6175

* T1: Nominal front time of impulse current and voltage.

T2: Nominal tail time of impulse current and voltage.

** Z : Impulse impedance.

3-2 Double-Layer Model

The dimensions of the used constructed aluminum tanks are 0.95 m X 0.95 m X 0.70 m for the bigger tank and 0.91 m X 0.91 m X 0.495 m for the smaller one. The water resistivity was changed by adding adequate amount of pure salt 7.1 Ω-m. Arrangement was made to keep the bigger tank on the floor and support the smaller tank on it. The bottom of the upper tank is 4 Cm below the top of the lower tank. The upper tank sides are isolated with a PVC sheet with a height 30 Cm from its bottom so that the current passes only through the base of the tank. The two tanks are connected to a test circuit similar to that in Fig. 1. A series of measurements were taken, so that five case studies (cases 6-10) were recorded and analyzed. The complete results of the five cases studied are shown in Table 2.

Table 2 Double layer experimental results

Case Study No.	Discharge Point	Measuring Quantities	16-Mesh grid without rods					16-Mesh grid with 25 rods				
			Shape Parameters				Z (Ω)	Shape Parameters				Z (Ω)
			Voltage		Current			Voltage		Current		
			V	T1/T2 (μs)	I	T1/T2 (μs)		V	T1/T2 (μs)	I	T1/T2 (μs)	
6	A	V_A, I_A	4900	0.501/4.74	63.06	0.451/4.835	0.7770	4718	0.334/3.12	70.13	0.693/3.71	0.6730
7	A	V_B, I_A	5020	0.481/4.60	63.30	0.351/4.79	0.7930	4680	0.43/3.72	68.31	0.281/3.55	0.6851
8	A	V_C, I_A	5080	0.334/4.60	63.90	0.484/4.51	0.7945	4720	0.334/3.955	69.80	0.476/3.71	0.6762
9	B	V_B, I_B	5020	0.392/4.57	64.69	0.501/4.9	0.7760	4680	0.250/3.625	69.54	0.184/3.695	0.6729
10	B	V_C, I_B	5080	0.409/4.63	64.61	0.434/4.78	0.7863	4720	0.42/3.8	69.11	0.334/3.71	0.6829

3-3 Triple Double-Layer Model

A third aluminum tank with dimension 86 Cm x 86 Cm x 50 Cm is used. The water resistivity is changed by adding a more amount of pure salt 6.05 ohm-m, 15 Cm height. An arrangement is made to keep the two tanks in the second model inside it. The bottom of the upper tank is 5 Cm below the top of the intermediate tank. The upper and intermediate tanks sides are isolated with a PVC sheet with a height 30 Cm from the bottom of them. A series of measurements were taken, so that five case studies (cases 11-15) were recorded and analyzed. The complete results of the five case studies are shown in Table 3.

Table 3 Triple-layer experimental results

Case Study No.	Discharge Point	Measuring Quantities	16-Mesh grid without rods					16-Mesh grid with 25 rods				
			Shape Parameters				Z (Ω)	Shape Parameters				Z (Ω)
			Voltage		Current			Voltage		Current		
			V	T1/T2 (μs)	I	T1/T2 (μs)		V	T1/T2 (μs)	I	T1/T2 (μs)	
11	A	V_A, I_A	4400	.418/2.74	90.35	.351/2.66	0.4870	4340	.484/2.12	88.39	.543/2.24	0.4910
12	A	V_B, I_A	4420	.418/2.675	90.29	.501/2.85	0.4895	4240	.418/2.08	85.95	.434/2.33	0.4933
13	A	V_C, I_A	4400	.443/2.643	90.33	.86/2.918	0.4871	4180	.267/1.93	84.32	.184/1.955	0.4957
14	B	V_B, I_B	4420	.376/2.72	90.76	.331/2.724	0.4869	4240	.351/1.89	86.34	.334/1.85	0.4911
15	B	V_C, I_B	4400	.418/2.800	90.52	.501/2.80	0.4861	4180	.267/2.05	84.29	.501/2.1003	0.4959

4- Impulse Impedance at Discharge Points

Either for 16 mesh grid or 16 mesh grid with 25 driven rods at the last intervals the impedance at discharge points can be evaluated by dividing the measured voltage by the measured current at that point. The impulse impedance values are tabulated in Table 4 for single, double and triple layers.

Table 4 Impulse impedance Z (Ω) for different measuring points

a- Single- layer

Measurement Point	16 Mesh grid	16 Mesh grid with 25 rods
Z_{AA}	0.75000	0.60000
Z_{BA}	0.75888	0.61714
Z_{CA}	0.7617	0.60767
Z_{BB}	0.75500	0.60130
Z_{CB}	0.77197	0.6175

b- Double- layer

Measurement Point	16 Mesh grid	16 Mesh grid with 25 rods
Z_{AA}	0.48700	0.49100
Z_{BA}	0.48950	0.49330
Z_{CA}	0.48710	0.49574
Z_{BB}	0.48690	0.49100
Z_{CB}	0.484610	0.49570

c- Triple- layer

Measurement Point	16 Mesh grid	16 Mesh grid with 25 rods
Z_{AA}	0.77700	0.67300
Z_{BA}	0.7930	0.6851
Z_{CA}	0.7945	0.67620
Z_{BB}	0.7760	0.6729
Z_{CB}	0.78630	0.67829

5. Conclusions

From the analyzed test results for the last mentioned models, it can be concluded that

- The single- and double-layer soils, impulse impedance decreases with adding rods. On the other hand, the impulse impedance is approximately unchanged value in the triple-layer soils.
- The addition of driven rods to the grid decreases the impulse impedance by the following percentages: 19.85% for single-layer soil, 13.75% for double-layer soils, and 1.25% for triple-layer soils.
- The impulse impedance value on all studied cases (grid with and without rods for single-, double-, and triple-layer soils) are approximately the same value either discharge points A or B or C.
- The presented results can be used to verify the mathematical models applied in substation grounding systems.

6. References

1. W. Xiong and F. P. Dawalibi, "*Transient Performance Of Sub-Station Grounding Systems Subjected To Lightning And Similar Surge Currents*", IEEE Trans. on Power Delivery, Vol. 9, No. 3, July 1994, pp. 1412-1420.
2. "*IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems*", IEEE std 142-1991
3. B. Phithakwong, N. Kraisnachinda, and M. Kando, "*New Techniques for the Computer-aided Design for Substation Grounding*", IEEE Power Engineering Society, Winter Meetings, Singapore, January 2000,
4. Z. Stojkovic, J. Nahman and D. Salamon "*Experimental Investigation of Grounding Grid Impulse Characteristics*", European Trans. on Electrical Power Engineering (ETEP), Vol. 8, No. 6, Nov./Dec. 1998, pp. 417-421

5. R. Caldecott, and D. Kasten, "*Scale Model Studies of Station Grounding Grids*", IEEE Trans. on Power Apparatus and Systems, Vol. PAS-102, No.3, March 1983, pp. 558-566

6. Impulse generator, Hipotronics, model: IG400-4 USA.

7. R. Velazquez and D. Mukhedkar, "*Analytical Modeling of Grounding Electrodes Transient Behavior*", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-103, No. 6, June 1984, pp. 1314 – 1322

8. R. Verma and D. Mukhedkar "*Impulse Impedance of Buried Ground Wire*", IEEE Trans. on Power Apparatus and Systems, Vol. PAS-99, No. 5, Sep./Oct.1980,pp. 2003-2007

9. S. Kannan and Y. Narayana "*Prediction Of The Parameters of an Impulse Generator for Transformer Testing*", Proc. IEE, Vol. 120, No. 9, Sep. 1973, pp 1001-1005

10. C. Mazzetti and G. M. Veca, "*Impulse Behavior Of Ground Electrodes*", IEEE Transactions on Power Apparatus and Systems, Vol. Pas-102, No.9, Sep.1983, pp. 3148 – 3156.