Determination Of Safety Distances From Ground Electrodes Subjected To Impulse Conditions

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DOI: 10.15598/aeee.v22i1.5336

Article history: Received Jul 28, 2023; Revised Jan 13, 2024; Accepted Jan 24, 2024; Published Mar 31, 2024.

Abstract. *When a high magnitude of current is discharged to the ground, a large potential gradient will result in a ground potential rise (GPR, or induced voltage. This GPR usually decreases with distances, depending on the soil resistivity, ground electrode sizes, configurations and steady state resistanceRDC values. The GPR value not only provides an information on the safe distance of the nearby equipment to the grounded electrical systems subjected to impulse conditions, but can also identify the right rating of the equipment, particularly sensitive electronic equipment, that are in a vicinity of the ground installations. Further, during the high voltage testing on the ground electrodes at field sites, the results may also be influenced by the electrodes under tests, which can cause inaccuracy in the measurements. This paper is therefore aimed to measure the GPR, where the measured results are still found to be limited in literature, for various soil resistivity and ground electrodes. The measured GPR values are obtained by injecting high magnitudes of impulse current of both impulse polarities on the ground electrode, and the voltage magnitudes at distances away from the edge of the electrode under impulse are measured. The measurements of GPR allows the investigations on the effect of impulse polarity on these GPR values, which cannot be obtained by computational method.*

Keywords

Ground electrodes, ground potential rise, ground resistances, impulse polarity, soil resistivity.

1. Introduction

Grounding systems need to be properly designed, so that, when there is a fault, the ground potential rise (GPR) is within an acceptable value. GPR is defined in IEEE Standard 80 [1], as 'The maximum electrical potential that a substation grounding grid may attain relative to a distant grounding point assumed to be at the potential of remote earth. The GPR values can reach several hundreds of volts, which some percentage of the GPR may be transferred through the ground wires, metallic pipes or through the soil to other grounding facilities in the vicinity of grounding grid where the fault current is discharged to. It is therefore important to determine not only the GPR values at the grounding grid, but also the transferred GPR to other nearby facilities, to ensure the GPR values are within the safety limits of equipment and personnel. IEEE Standard 367 [2] provides comprehensive guides on the calculation of GPR and induced voltage for the telecommunication facilities at and near the electrical facilities, taking into account several parameters, among which are; impedance of the electrical facilities the fault current and zone of influence, defined as ZOI. Due to many factors and considerations used in the calculation, particularly considering the real systems, complex calculation is involved.

Previously published work [3,4] determined the GPR values for various configurations, soil resistivity, and they found that; GPR is high in high soil resistivity, high current magnitudes and high resistance value. Several studies [3–8] have also been carried out on the GPR values at some distances from the grounding grid of various configurations and soil resistivity. Using CDEGS), Pretorius [3] found that GPR values reduce for a distance of 50 m to 100 m from the strike point of the electrode, and the percentage reduction of these GPR values is the highest for the lowest soil resistivity. However, for the same soil resistivity, little difference is seen in percentage reduction for small, intermediate and large grounding grids. All of these studies are needed to provide information for the safe distance of other equipment, underground cables, humans who may be in the vicinity of the grounding grid under strikes. With the information of GPR values, rating and withstand capability of the nearby equipment can be set adequately, so as to avoid damage to the equipment due to exposure to these high GPR values.

Steps and calculation in obtaining GPR, touch and step potentials have been presented in the standards [1] particularly for the large scale ground grids (i.e. substation), and these safety voltage limits change with time and body weights. These safety limit may not be achievable for small scale ground electrodes due to small size of ground electrode, hence producing high resistance value, correspondingly giving high GPR. Due to that, the safety design criteria for grounding systems presented in the standards are not very much practical for small scale grounding systems. The number of units of these small scale grounding systems is also huge, making it unrealistic to meticulously follow the steps as in the standards, hence the approach is more towards obtaining the desired low ground resistance value, as a basis of the safety limits, where the lower the ground resistance values, the lower the GPR values are. Further, small scale grounding systems are normally used for small systems level, of below 11 kV and, where it was reported that the fault current limit associated for these systems is below 13 kA [9] for 11 kV systems, and higher short circuit rating of 20 kA has been proposed in [10] for 11 kV systems. Therefore, the steps and design consideration on the 11 kV grounding systems are not strictly following the design steps used for higher systems level.

Due to the reasons that the studies so far, are mostly performed by computational method, and no detail document of the test set up and measurements of determination of GPR values can be found in literature in regards to small scale systems, this paper is aimed to present the GPR values by field measurements, for six ground electrode's configurations, installed at two test sites, and subjected to positive and negative impulse polarities. These measured induced voltage values can be used to determine whether the nearby electronics equipment can withstand these induced voltages. With these techniques, it is hoped that the electronic equipment that are located near to the substations or electrical utilities, higher rating of the electronic equipment can be determined, and considered due to possible high GPR values. Measurements of the voltage at and in the vicinity of these ground electrodes used in this paper provide a similar case of the voltage that may rise at and in the vicinity of small scale ground facilities, such as street lighting poles, residential and buildings. These facilities are easily accessible by the public, and may harm the nearby personnel and damage the equipment if the voltage rise is beyond the equipment safety limits and human body tolerance. Other than that, the GPR can be useful to determine the distances to place the voltage and current instruments from the ground electrode under impulse tests by field measurements so that the measurement results are reliable and accurate, and not influenced by the GPR values.

In this work, other than the measurements of the GPR, Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis (CDEGS) is also utilized to compute for GPR values for various ground electrodes subjected to impulse conditions. This paper shows that with the measurements and computational of the GPR, some considerations can be given on the safety margins of the facilities at the vicinity of the grounding installations, and provide reliable and accurate test results during high impulse tests on ground electrodes.

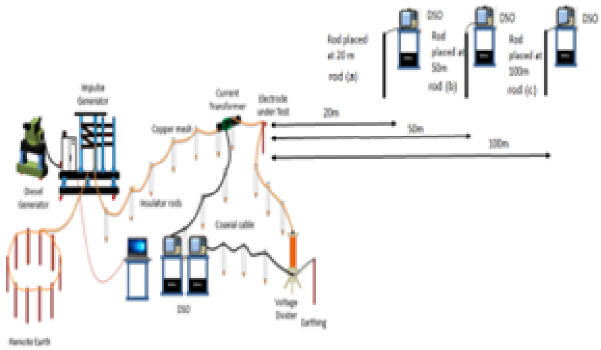

Fig. 1: Test set up used to measure the induced voltage at distances away from the ground electrode under test.

2. Test Arrangement and Computational Method

2.1. Testing Equipment

Fig. 1 shows the test set up used in the study. Impulse generator is used to generate high voltage magnitudes, current transformer with the ratio of 0.01 V/A is used to measure for the current and resistive divider with the ratio of 3890:1 is used to measure for the high voltage. These current and voltage signals are captured by Digital Storage Oscilloscopes (DSOs). Two test sites and five configurations used are similar to that used in Ref. [11]. The soil profiles of both sites are approximated into two-layer soil model, using Current Distribution, Electromagnetic Interference, Grounding and

Soil Structure Analysis (CDEGS) with the top layer of 57.2 Ωm, with the depth of 6 m, and soil resistivity of bottom layer of 758.1 Ωm, for site 1, while site 2 has a much lower soil resistivity with top layer of 3 Ωm, with the depth of 4.9 m and 0.2 Ωm for the bottom layer. Both sites having an infinite depth for the bottom layer.

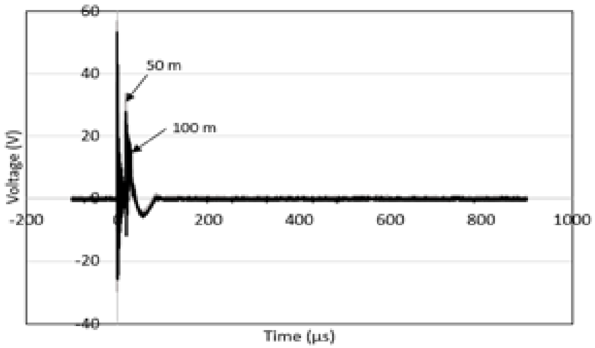

Fig. 2: Measured voltage traces at various distances from a single rod electrode, installed at site 1, injected at 100 kV.

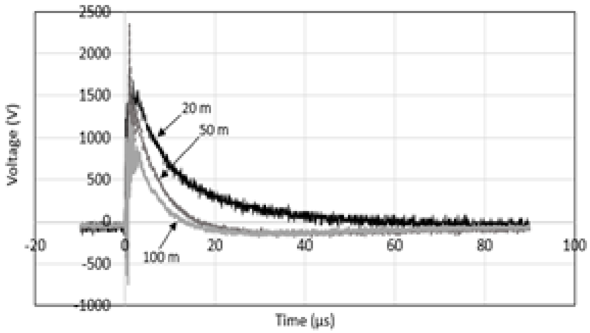

Fig. 3: Measured voltage traces at various distances from a single rod electrode, installed at site 2, injected at 100 kV.

2.2. Ground Electrodes Subjected to Impulse Conditions

Table 1 presents some details of the ground electrodes used, this information is a reproduced table from Ref. [11]. Similar remote earth as presented in Ref. [11], is also used in this study. Each rod electrode consists of 16 mm diameter, with the length of 1.5 m. For the of the reader, brief description on the construction of the electrodes is included here. Configuration (1), comprises of a single rod electrode of 16 mm diameter, with the length of 1.5 m configuration (2) is a 2-parallel , the single rod electrode (1) is another rod electrode with copper strip of 2 cm width, thickness of 2 mm the length of 3 m. (3) is laid in similar arrangement to configuration (2), but 3 single rod electrodes. (4) is a grounding device with spike rods (GDSR), of 4 cm diameter rod 1.5 m length. The GDSR has an inner shaft, with a handle at the top end, which can be turned to protrude out 5 spike rods of 1.5 mm, each with the length of 17 cm. (5) a GDSR, 2 parallel rods, as configuration (2).

Tab. 1: Ground electrodes and its corresponding RDC (Reproduced from [11])

Conf. No.	Ground Electrode	$R_{DC}(\Omega)$	
		Site 1	Site 2
1	1-rod electrode	104.4	75.5
2	2-parallel rod electrode	44.8	27.6
3	3-parallel rod electrode	28.5	17.8
4	1 Grounding Device with Spike Rods (GDSR) in parallel with 1-rod electrode	37.6	14.6
5	1 GDSR in parallel with 2-rod electrode	26.6	11.3

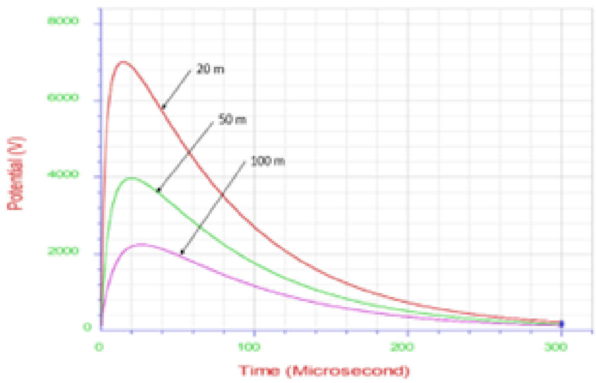

Fig. 4: Computed GPR values at various distances from configuration 5, installed at site 1 injected at 4 kA.

All of these electrodes are subjected to increasing impulse voltage, induced voltage levels measured. The resistance values at power frequency, RDC are measured with a Fall-of-Potential (FoP) method, where the values are presented in Table 1 can be seen clearly that the larger the dimensions of the ground electrodes, the lower the RDC values . The remote earth, which provides the current path to the ground comprises of 10 rod electrodes, each of 16 mm diameter, 1.5 m length, arranged in circular to a diameter of 10 m. All the tested electrodes and remote earth are buried 0.3 m below the ground's surface.

For the measurements of the induced voltage levels, three single rod electrodes, each of 16 mm diameter 1.5 m length, are installed at 20 m, 50 m and 100 m from the impulse generator, labelled as induced rod electrode (a), (b) and (c) respectively. All the induced rod electrodes are buried to 1 m depth. Voltage measurements are achieved with three high voltage (HV) probes each with a ratio of 1000:1, which is connected to an individual DSO. It should be noted, and Fig. 1, that, there no direct connection of these single rod electrodes (a), (b) and (c) to any of the equipment, ex-

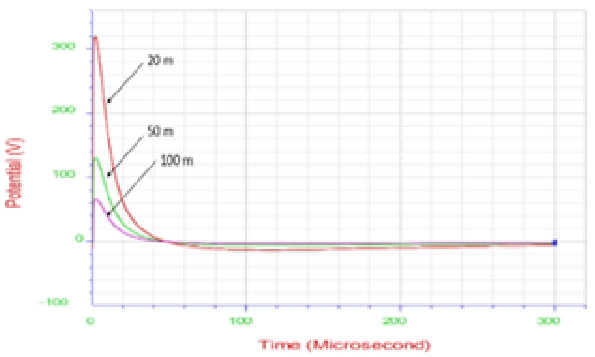

Fig. 5: Computed GPR values at various distaces from configuration 5, installed at site 1 injected at 16 kA.

cept to the HV probes and to the DSOs. Impulse tests with increasing voltage magnitudes under both positive and negative impulse polarities are applied on configurations (1) to (5), and the voltage measurements are taken from the single rod electrodes (a), (b) and (c). This set up is to provide a preliminary study of the measurement of the voltage at distances away, due to conduction in soil. It is noted that voltage rise may be induced from the above structure/ground electrodes that have been presented in other literature [12] before. This paper is to provide a preliminary study, of the rise in voltage, only from the soil conduction point of view.

2.3. Computational Method

A standard lightning waveform with maximum magnitude currents, I_m of 4 kA and 16 kA respectively for electrodes installed site 1 and site 2. These are the highest current magnitudes exhibited in the ground electrodes presented in Table 1 [11], these current magnitudes generated with Fast Fourier Transform (FFTSES)-CDEGS module in Eq. (1). The soil resistivity values are as presented in section 2.1 and the ground electrode configurations as presented in section 2.2.

$$I(t) = I_m \left(e^{-\alpha t} - e^{-\beta t}\right),$$
$$\alpha = 1.426 \times 10^4 s^{-1},$$
$$\beta = 4.877 \times 10^6 s^{-1}. \qquad (1)$$

3. Test Arrangement and Computational Method

3.1. Experimental Results

Figs. 2 and 3 show the measured induced voltage at distances away from the electrode under tests (configuration 1) respectively for site 1 and 2. no observable effect is seen in the measured induced voltage for single rod electrode (a) installed at site 1 when configuration 1 subjected under high impulse conditions. Similar traces are seen when other configurations are installed at site 1, due to very low magnitudes of measured induced voltage. On the other hand, higher measured induced voltage magnitudes are seen for site 2, and these magnitudes are found to be dependent on several factors, voltage magnitudes injected to the main ground electrodes (1) - (5), distances from the ground electrode under strike and impulse polarity. Low voltage magnitudes observed in site 1 due to its high soil resistivity, thus only induced voltage values from site 2 are and presented in this paper. Impulse polarity effect investigated for site 2, and it noticed that induced voltage values are not affected by the polarity (Table 2). It also in the study that the induced voltage values are not influenced by the RDC values, close induced voltage values were measured for all configurations. This finding is found to be contradictory to the typical observation seen in previously published work [6], who found that the lower the RDC of the grounding grid, the lower the GPR or induced voltage magnitudes are, hence lower voltage magnitudes radiate away from the grounding grid.

4. Computational Results

Figs. 4 and 5 show GPR traces computed for 20 m, 50 m and100 m when configuration 5 installed respectively at sites 1 and 2. As expectedly seen in the measured GPR values, presented earlier in section 3.1, the GPR values were found to reduce as the distances from the ground electrodes subjected to impulse conditions are increased. For the same configuration, it can be seen that GPR of configuration 5 installed at site 1 are higher than that installed at site 2. Also configuration 5 installed at site 1 reduces to zero at a slower time than the electrodes installed at site 2, despite higher current magnitude was applied to electrodes. This could be due to lower soil resistivity at site 2. For other electrodes installed at site 1, traces are similar to Fig. 4, while other electrodes installed at site 2 have similar responses to Fig 5.

Table 3 summarises the maximum GPR values for all electrodes. Based on the basic formula of GPR which is dependent on the magnitude of current entering the ground electrode and the ground resistance value, RDC, it can be seen from the table that higher GPR values are seen for the same electrodes installed at site 1, due to high soil resistivity and ground resistance values, RDC. The trend on the GPR values dependent on the RDC values is also seen in previously published work [13], where the higher the RDC values of the transmission tower, the higher the GPR values

Tab. 2: Measured induced voltage for ground electrodes subjected to positive and negative impulse polarities.

Conf No	Positive Impulse Polarity				Positive Impulse Polarity			
	Vapp (kV)	20m (V)	50m (V)	100m (V)	Vapp (kV)	20m (V)	50m (V)	100m (V)
1	9.52	800	700	400	13.4	780	600	300
	16.6	1440	1260	700	24.2	1620	1300	860
	23	2280	2200	1200	32.2	2440	2200	1250
	25	2640	2400	1600	40.4	2800	2500	1500
	29.4	3760	2880	1840	46.8	3400	2800	1800
	34.2	4320	3600	2240	52.4	4000	3360	2240
2	9.52	704	632	400	9.68	730	600	450
	16.6	1800	1380	1100	16.6	1500	1300	1000
	23	2200	1500	1500	22.6	2200	1880	1480
	25	2720	2200	2000	25	2720	2500	1960
	29.4	3360	2800	2200	29.8	3500	3000	2320
	34.2	4000	3200	2960	33.8	3800	3200	2800
	38.2	4640	4000	3000	39.4	4560	3840	3100
3	7.28	720	580	500	7.76	750	632	500
	13.4	1600	1250	1000	13.4	1500	1200	1100
	14.9	2000	1500	1320	15	2000	1700	1400
	19.6	2900	2100	2000	20	2800	2500	2080
	24	3440	2800	2440	23.8	3200	2800	2480
	27.2	4500	3500	3200	27.4	4000	3200	2800
4	9.6	840	624	400	9.2	780	600	400
	17.8	1700	1200	1000	17.4	1640	1400	1000
	25.6	2300	1800	1500	25.8	2500	2000	1500
	27	2800	2200	1800	27.4	3000	2400	1800
	33.8	3600	2800	2300	33	3800	3000	2200
	39	4200	3440	2800	38.6	4200	3800	2800
	44.2	4800	3800	3000	43.4	4800	4000	3000
5	7.12	780	600	450	7.04	780	688	500
	12.6	1500	1300	1000	13	1500	1400	1250
	17.8	2250	1800	1500	17.6	2400	1960	1620
	19	2900	2000	2000	19.2	2800	2500	2000
	23.4	3360	2800	2500	22.8	3300	2800	2500
	27	4000	3200	3000	26.8	4000	3440	2600
	31	4600	3840	3200	30.8	4800	4000	3000

are. From the basic GPR formula, the product of current entering the ground electrode, I and the ground resistance, R, expectedly the higher the current magnitudes, the higher the GPR values are. In this work, despite ground electrodes at site 2 were subjected to four times higher current magnitudes than those at site 1, higher GPR values of electrodes installed at site 1 was seen in comparison to site 2. This is thought to be due to high soil resistivity at site 1, hence higher RDC values. resulting in higher GPR values than the electrodes installed at site 2. The GPR values for all electrodes installed at site 1 were found to be approximately 100% higher than the electrodes of the same configuration installed at site 2, despite the RDC values between electrodes installed at site 1 and 2 were differ not more than 65%. It can be seen here that despite the current magnitudes have an effect on the GPR values, the effect of soil resistivity, hence RDC values are more significant in influencing the GPR values than the current magnitudes.

When the percentage difference between the maximum GPR values were compared between the distances, it was noticed that ground electrodes installed at site 2 are 26% and 12% higher respectively for the distance between 20 m and 50 m, and 50 m and 100 m than the electrodes installed at site 1. Higher percentage difference between the distances for site 2 could be due to lower soil resistivity at site 2, hence decreasing the GPR values at a faster rate than the electrodes at site 1.

5. Conclusion

In this work, both positive and negative polarity impulses with increasing applied voltages were applied to five ground electrodes, installed at two sites, and its corresponding induced voltages were measured and computed at a distance of 20 m, 50 m and 100 m from the ground electrodes under impulse tests.

Very low measured induced voltage magnitudes and noises only were seen in the measured GPR responses for electrodes installed at site 1 which is taught to be due high resistivity soil of site 1. Analysis was then only considered for electrodes installed at site 2, where the following conclusions can be made; (i) the further the distance from the ground electrodes under impulse, the lower the induced voltage magnitudes are, (ii) the higher the RDC of the ground electrode under impulse, the lower the induced voltage magnitudes are, and (iii)

Tab. 3: Computed maximum GPR values for various ground electrodes subjected to impulse current

Site	Conf.	Distance (m)			Diff. between 20 m & 50 m (%) for various conf.	Diff. between 50 m & 100 m (%) for various conf.
		20	50	100		
1	1	7564.5	4152.8	2311.3	45	44
	2	7269.8	4061.8	2279.6	44	44
	3	7004.1	3977.4	2250.2	43	43
	4	7286.4	4067.0	2281.4	44	44
	5	7022.6	2281.4	2252.2	43	43
2	1	337.6	134.0	66.7	60	50
	2	320.9	131.0	65.9	59	50
	3	318.0	130.3	65.7	59	50
	4	322.3	131.3	66.0	59	50
	5	319.7	130.6	65.8	59	50

induced voltage magnitudes are found to be independent of impulse polarities. All of these findings indicate that there is a need to measure the induced voltage magnitudes, to provide safety distance and identify the right rating of equipment, cables, telecommunication systems which are in vicinity of grounding installations.

For computed GPR traces, the trend also shows that the further the distances from the ground electrode subjected to impulse conditions, the lower the GPR values are. However, a contradictory result between the measured and computed GPR values, i.e. for the same electrodes, higher computed GPR values are seen for electrodes installed at site 1, whereas for the measured GPR values for electrodes installed at site 1, GPR traces were hardly captured and consisted only noise in the signals due to its low GPR values in comparison to those electrodes installed at site 2. Other interesting result can be seen from the computed GPR values is that for the same electrode's configuration, GPR values decreased at a faster rate for ground electrodes installed at site 2 than site 1, despite current magnitude injected to the electrodes at site 2 is four times higher than that injected to the electrodes at site 1. This is thought to be due to high soil resistivity at site 1, causing slower discharged time for electrodes at site 1. This also indicates that the soil resistivity gives more significant effect in the GPR values than the current magnitudes.

In summary, despite the challenges in obtaining the measured GPR values for the high resistivity soil (site 1), observable difference in the impulse polarity effect and the limited impulse generator's rating, where higher rating can be considered particularly to observe for high resistivity soil, this study has successfully demonstrated that the safety of grounding system depends on other factors besides low resistance value, RDC. Measured and calculated induced voltage magnitudes can be used to establish the adequacy of grounding system which will be clearly important in deciding the separation distance between the grounding installations to equipment in a vicinity, and whether the rating of nearby equipment can withstand these induced voltages, when the grounding installations at distances are subjected to impulse conditions.

As the experimental results are different than those obtained by computational studies, it is therefore necessary to extend the experimental investigations of various soil conditions (the effect of soil structure where higher soil resistivity at top layer than the bottom layer, and vice versa), different ground electrode's configurations and higher rating of impulse generator.

Acknowledgment

This research was funded by MINISTRY OF HIGHER EDUCATION OF MALAYSIA (MOHE) under Fundamental Research Grant Scheme (FRGS), grant number FRGS/1/2021/TK0/MMU/02/8 and TELEKOM MALAYSIA RESEARCH DEVELOPMENT (TMR&D), grant number MMUE 210072.

Author Contributions

U.M, F. A. and S. A run an experimental and simulation work. N.N supervised the work, checked the results and contributed to the final version of the manuscript.

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