30th International Conference on Lightning Protection - ICLP 2010
(Cagliari, Italy - September 13th -17th, 2010)

HIGH FREQUENCY EARTHING IMPEDANCE MEASUREMENTS AT CAMP BLANDING, FLORIDA

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ABSTRACT

This paper intends to relate high frequency earthing impedance measurements made on the earthing systems installed at Camp Blanding Florida to the sharing of current measured during triggered lightning tests at the facility.

1 INTRODUCTION

High frequency earthing measurement techniques are now well known as well as the benefits gained from their use. However, there are only few instances where there has been an opportunity to compare measured grounding system impedance with data recorded during actual lightning events. Much of the initial information used to confirm the results obtained from high frequency earthing impedance testers is based on comparison of measured data from specifically designed earthing systems (typically for telecom applications) with simulations of the expected response of the grounding system. More recently, a device using the injection of surge current was compared with one of the devices measuring selected frequencies of up to 1 MHz [1]. It was found that these devices yielded similar results. Comparisons with real lightning data were still missing so an attempt was made a few years ago to make impedance measurements at Camp Blanding in Florida to take advantage of the vast amount of lightning results registered at the research facility. However, due to the dryness and high resistivity of the sand-based soil at the site, the device failed to provide any valuable measurements. Since that time the measuring techniques have been refined and a second generation device used satisfactorily in other sandy places in the world has been developed. A second attempt was made in April 2009 to try to obtain usable measurements with this new device and measuring technique. The purpose of this effort was to make measurements at various locations in the Camp Blanding facility, especially around the test house, in order to:

a) relate the measured earthing impedance results to the configuration of embedded earthing systems which was documented at the time of installation and

b) use the network of measured impedances to predict the sharing of current between the various earthing points (test house, earthing at the remote end of the power cable, etc.).

The results of these measurements will then be compared with what has been measured during triggered lightning tests. The measured lightning testing results used in this analysis will be taken primarily from three published papers. The first paper deals with direct lightning strikes to the lightning protection system of a small dummy residential building [2]. The second paper discusses lightning testing of the performance of grounding systems in Florida sandy soil [3] and the third paper describes the distribution of currents in the lightning protection system of a small residential building [4], documenting the 2004-2005 test house experiments.

While the 2009 impedance measurements were conducted in April, which is not the driest part of the year, the sand was still very dry and exhibited high resistivity; making measurements difficult. For several test locations, the first measurements at the lower frequencies yielded no results but as the capacitive behavior of the grounding system became noticeable at frequencies above 63-100 kHz, measurements were always possible. DC measurements using a standard low frequency earth resistance tester were also made to compare with data recorded in 2005 during the triggered lightning tests. Some of the measurements were made with aligned injection and measurement electrodes in two different axes to facilitate comparison and to gain some confidence in measured results.

2 TESTING EQUIPMENT AND PROCEDURES

High frequency measurements of earthing impedances were performed using an AES 1002 meter manufactured in France [1][5]. It allows measurement of the impedance of an earthing electrode or complete earthing system within a range of frequencies from 79 Hz to 1 MHz. It does this using a standard three point measurement configuration with an injection electrode (z) and a measuring electrode (y) aligned and with the measuring electrode located at 66% of the distance between the injection electrode and the earth electrode under test (x). The difference between this tester and other 3-point fall of potential testers is that coaxial cables are used to connect the electrodes to the test instrument to take care of the high frequencies used and that the test is conducted at 20 different frequencies. The coaxial cables currently limit the length of the z cable and y cable to 15 m and 10 m, respectively. In this text, the group of injection electrode (z) and measurement electrode (y) is named reference electrodes.

Due to the poor soil conditions and porous nature of the local sand, the contact between the reference electrodes (y and z) was anticipated to be an issue in this testing. It was found to be helpful to pour some water at the injection and measuring electrodes when making the measurements because this improved the contact between the reference electrodes and local soil. After making some measurements without adding water (normal conditions) it was decided that some water should be added around the immediate vicinity of the reference electrodes and the results compared with the higher frequency values of those tests without water to ensure there is no bias in the data. Using small quantities of water (typically less than 1 liter) in the immediate vicinity of the reference electrodes did not significantly change the test results but did improve the quality of the measurements. Such a procedure has been used in the past in some circumstances; especially in sandy soil and dry conditions.

The interpretation of the results from the testing is given in terms of the quality of the high frequency earthing impedance as well as the plot of the measured impedance (Zm) versus frequency. It was decided that it would be interesting to also document the peak values recorded (especially those at frequencies of 63 kHz or higher) as well as the mean value (average impedance) from 63 kHz to 1 MHz [6].

According to standards, the conventional earthing impedance is "the ratio of the peak values of the earth-termination voltage and the earth-termination current which, in general, do not occur simultaneously". The average impedance given by the device is similar to the "conventional earthing impedance" that standards define and use for example for current sharing between various earthing electrodes.

3 TEST POINT LOCATIONS

After review of the comparison data available [2][3][4], it was decided that measurements should be made:

- at the test house (see Figure 1)

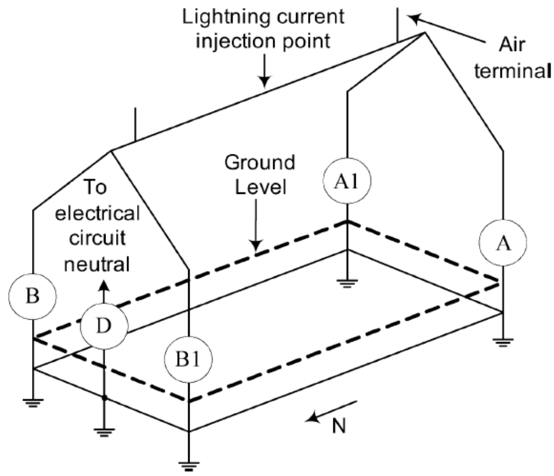


Figure 1. Test house (2005) [4].

Figure 2. Test house picture (2005).

- at the old simulated house (seen at the lower right corner of Figure 2)
- at earthing locations at the tower
- at Instrument Station 1 (IS1) earthing point (at the end of the 600 V cable connected to the test house (see Figure 3))

In order to keep the same numbering as in 2005 and to avoid confusion between current measuring locations in

2005 at the test house and measured electrodes from 2009 measurements, we have decided to name the electrodes located below the measuring point A, B, A1 and B1 : EA, EB, EA1 and EB1, respectively. Since IS1 has an electrode, we will keep the same designation in 2009 as in 2005. The last rod measured in 2009 at the test house is referred to as the utility rod (below point D in figure 1).

It should be noted that the measurements are made without disconnecting the link to the rods. So, when we make a measurement at electrode EA location for example, we are in fact measuring the impedance seen from EA. This includes of course electrode EA but also a part of the counterpoise and a part of the other rods, this part depending on the frequency of the injected signal. At highest frequencies, the inductive effect of the counterpoise limits the current injected in the counterpoise and the measurements mainly relates to the local rod EA where the device is connected. On the other hand, the average impedance gives a mix of all the electrodes (rods, counterpoise) connected at this place with more emphasis on electrode EA.

Table 1: Earthing impedance measurement made in 2009.

N°	**Location of measurement point**	**Water poured on electrodes**			**Measured impedance (Ω)**	**Measured impedance (Ω)**	**Comments**	**Location of measurement point (x) and injection/measurement points (z/y) see Figure 5**		
		x	**y**	**z**	**@ 63 kHz**	**@ 1 MHz**		**x**	**y**	**z**
3	EB1	No	water	water	919	186		NW	45° NS axis A direction	45° NS axis A direction
4	EB1	water	water	water	84	121	same than 3 except with water	NW	Same as above	Same as above
5	EA	No	water	water	64	134		SW	Same as above	Same as above
6	EA	No	water	water	716	48	measured on down conductor side - disconnected	SW	Same as above	45° NS axis B1 direction
7	EA	No	water	water	716	162	measured on earth side with connector disconnected	SW	Same as above	Same as above
8	EA	No	water	water	718	159		SW	Same as above	Same as above
9	EB	No	No	No	727	215		NE	middle	Old simulated house
10	EB	No	water	water	713	194		NE	Same as above	Same as above
11		water	water	water poured during M10 measurement only	-	370	Y remains the same but Z is now located on B	Old simulated house	Same as above	NE
12		water	water	water	-	341		Old simulated house	middle	Tower rod
13		water	water	water	627	132		Tower rod	Same as above	Old simulated house
14	IS1	water	water	water	-	227		IS1	Axis NW	Axis NW
15	IS1	water	water	water	-	193		IS1	Axis NE	Axis NE
16	Utility rod	water	water	water	-	284		power rod	Axis NW	Axis NW

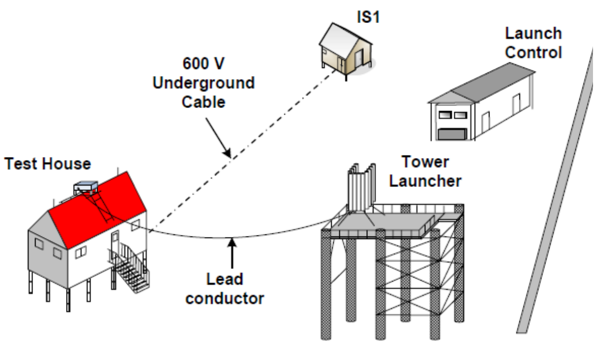


Figure 3. Test layout (2005).

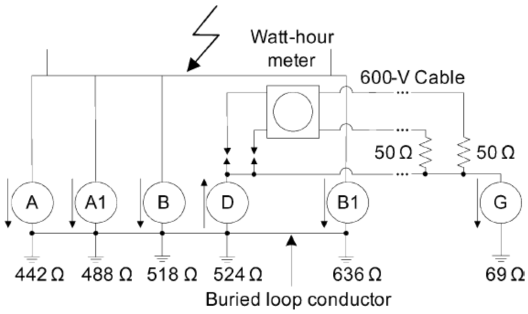


Figure 4. Test house equivalent diagram (2005) [4].

4 ANALYSIS OF TEST RESULTS

Results obtained at the test house in 2009 are given in Table 1. Measurements 1 and 2 were confirmation measurements used for setting up the device. The earthing system (all connected) resistance was measured with Camp Blanding's Biddle earth resistance meter and a low frequency resistance to remote earth of 175 Ω was recorded. This value was considerably higher than the 113.4 Ω value recorded during the 2004 testing when the grounding system consisted of a pair of interconnected driven ground rods installed at both the northeast and southwest corners of the test house [3] and the 121 Ω value recorded before the 2005 test season when the grounding system was modified as shown in Figure 1 to include a single driven ground rod at each corner of the structure with an interconnecting ground ring electrode.

The significant difference in data suggests an apparent degradation of the grounding system with time and climatic conditions or, more likely, a significant variation in earth resistivity at the site depending upon the moisture content of the sand. The differences between the values recorded in 2004 and 2005, although for different geometries, may suggest the change in earth resistivity due to soil moisture is indeed the dominant factor. Despite the intended improvement of the earthing system for the structure, the measured resistance to earth value from 2004 to 2005 was found to increase and not decrease as could be expected.

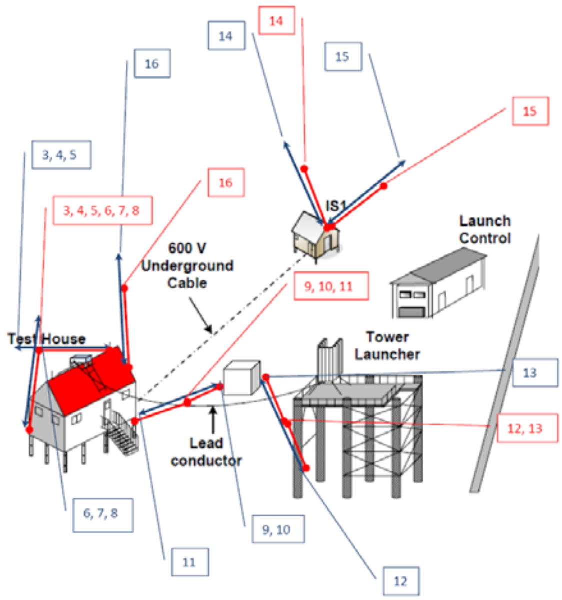
In 2005, the value for each earthing rod was measured and is given in Figure 4.

Table 2 provides a comparison of the low frequency earthing rod resistances measured in 2004 and 2005. IS1 remained the same, EA and EB degraded while the utility rod improved.

Table 2: Comparison of measured earthing rod resistances [4].

Electrode number	2004 (Ω)	2005 (Ω)
EA	336	442
EA1	-	488
EB	468	518
EB1	-	636
Utility rod	668	524
IS1	69	69

Figure 5 gives the location of reference electrodes (y) and (z) for each of the measurement described in Table 1.



Key:
Blue – (z) electrode
Red – (y) electrode
Square – measurement number

Figure 5.Location of reference electrodes (y) and (z) (see Table 1)

From a review of high frequency measurements,, we can observe that measurement M4, made with water added around the electrode under test (EB1), yielded a substantially better result than an earlier measurement without water at the same location (M3). Originally, rod EB1 was the overall worst earthing electrode tested and with water it appeared to be not so bad.

Measurements M5 and M8 are taken from the same electrode in the same configuration. Electrode EA was first measured interconnected with the others through the down conductor network and earth ring conductor (M5), then the test joint was opened and a measurement was made on the down conductor side of the test joint (M6), on the earthing rod side of test joint (M7) and then the system was interconnected again (M8). Even if values at 1 MHz are not so different between M5 and M8, the values at 63 kHz differ greatly. The primary reason for this discrepancy is likely the difference in the location of the reference electrodes. For M5, electrodes y and z were located at the same place as for M3 and M4, thus creating a line EB1-(y)-(z). The electrode configuration EA-(y)-(z) was not in a line and the value could have been influenced by the proximity of the y and z electrodes to the earth ring conductor. The reference electrode configuration was readjusted for measurements M6 through M8. M5 is clearly too favorable and not realistic compared to other measurements and may have been influenced by a radial conductor from the 2004 installation, located near electrode A, which was disconnected but still in the ground (see Figure 6).

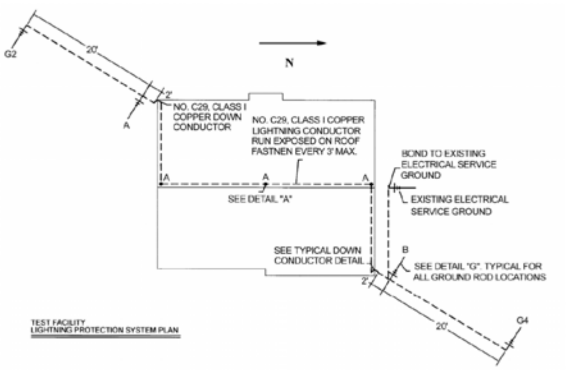


Figure 6. 2004 earthing layout.

Different values obtained at 1 MHz, depending on the measuring point, are interpreted as various ringing effects between the rods (mainly capacitive due to their small length) and the inductive effect of the buried loop conductor and down conductors on the roof. While M6 shows a rather smooth curve (see Figure 7), M7 and M8 are quite erratic with various high and low values (Figures 8 and 9). This is typical of the device having difficulties determining the zero crossing and thus the phase angle.

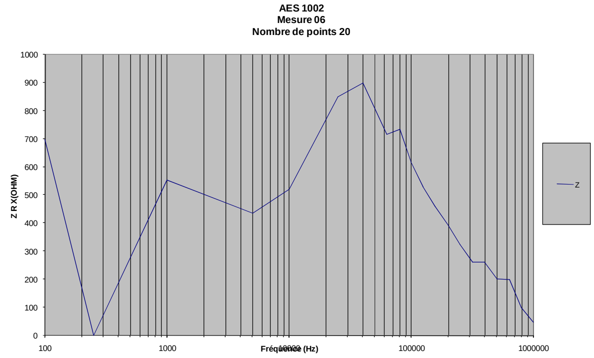


Figure 7. M6 Z .vs. frequency curve.

The plots of M7 and M8 are very similar. M7 was measured on the grounding side with the connector opened and M8 at the same location with the connector closed. The test results from M7 and M8 indicate that the interconnection with the down conductor had a negligible effect on the impedance to earth due to the inductive effect of the down conductor network.

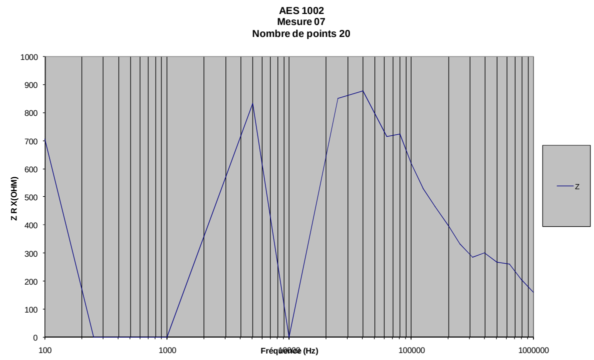


Figure 8. M7 Z .vs. frequency curve.

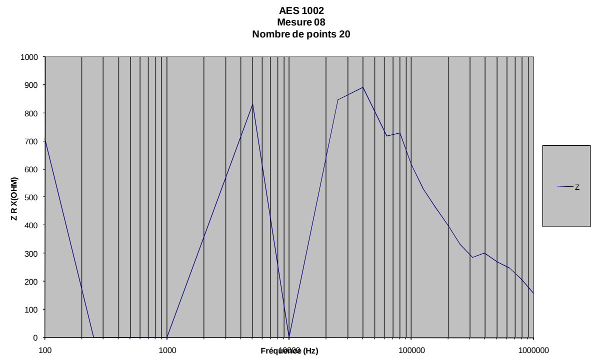


Figure 9. M8 Z .vs. frequency curve.

When measurement M6 was made on the other side of the opened test joint, the impedance seen was quite different. The average value of impedance decreased from 405 Ω for M7/M8 to 373 Ω for M6. There is an inductive effect in series with the earthing network which should increase the impedance of M6 instead of decreasing it. It is likely that resonance between various lumped elements in the circuit make the impedance lower at high frequencies. It should be noted that the device is able to discriminate between an open and closed test joint. Using the same test point and measuring technique, the curve pattern is clearly different between plots for M6 and M7. It has not been possible to measure each rod individually with a regular low frequency meter due to the earthed ring conductor connecting all electrodes together but it would be interesting to excavate the various rods and determine possible reasons for such a different behavior between rods: resonance or different conditions of rods in terms of corrosion and resistance of contact. Original 2004 and 2005 low frequency resistance measurements have shown that the rod embedded at the southern part of the test house had lower resistances than the ones at the northern part (including the utility rod).

Measurements M9 and M10 made at earthing point EB (see Table 1) show a less dramatic effect of pouring water on the y and z electrodes. However, it should be noted that for these two measurements, the earthing system of the original test house (known colloquially as Joe's house) was used as reference electrode z. This earthing rod was driven much deeper than any of the other reference electrodes (even though the resistance measured in 2009 on the rod was > 2000 Ω). The much deeper reference electrode is likely the primary reason the effect of water on the reference electrodes is minimized. The effect of adding water around earthing electrode EB before the measurement was not found to be as important as it was for EB1. The average impedances of M9 and M10 varies only from 433 to 424, respectively, but the curve is smoother for M10.

The last measurement on the test house was at the utility rod (M16). Resistance measured in 2009 at this location was > 2000 Ω even though 524 Ω was recorded in 2005. There was evidence that the rod may have been degraded since the 2005 test season. Impedance values could not be measured at frequencies below 100 kHz. The average impedance was found to be 593 Ω. This result was obtained by pouring water on the electrode under test in order to compensate for the large value of the resistance. For the remaining measurements, water was added around both the reference electrodes (y and z) as well as the electrode under test (x).

Measurements M11 and M12 were made on the old simulated house. While M11 was measured using the new test house electrode EB as reference electrode z, M12 uses the tower rod (which is near) as electrode z. In both cases, electrode z is a much better electrode than the usual injection reference rod. Average values obtained varied from 628 Ω to 633 Ω, respectively. As can be seen in Table 1, values at 63 kHz couldn't be measured; confirming the fact that this earthing rod is not a good one and has probably degraded with time. Resistance at the time of installation can be found in [2] to be 1550 Ω for the worst case (and tens of ohms at the end of testing in 1997), while the resistance measured in 2009 exceeded the measurable range of the test equipment (> 2000 Ω).

In contrast, the earthing at the launch tower had a measured resistance of 36.4 Ω, which is pretty good for such a dry and sandy soil. Measurement M13, made at this location using the original simulated house earthing electrode as the injection electrode (z), was found to have an average impedance of 343 Ω and the curve is pretty smooth as can be seen in Figure 10.

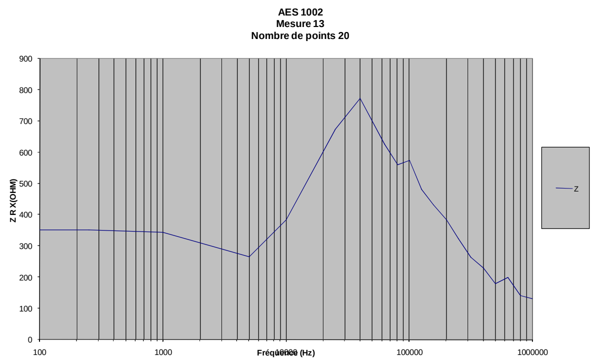


Figure 10. M13 Z .vs. frequency curve.

The last two values (M14 and M15) were measured at the Instrument Station (IS1) at the other end of the power cable entering the test house. The resistance measured in 2004 at this location was 69 Ω. The only difference between M14 and M15 is the location of the y and z electrodes. The resistance measured in the 2009 testing for this location was 137 Ω. The average impedance measured for M14 and M15 are 495 Ω and 467 Ω, respectively, and the impedance versus frequency plots are very similar (see Figure 11). Data could not be obtained at frequencies less than 80 kHz.

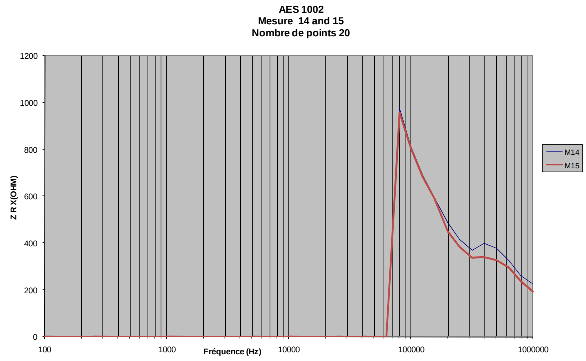


Figure 11. M14-M15 Z .vs. frequency curve.

All usable data obtained in 2009 show a capacitive behavior (impedance decreases with frequency) at the highest frequencies, which is not unexpected in such a high resistivity soil where current has difficulties to enter deep in the soil. When we compare measurements made on the test house in 2005 and new data at 63 kHz and 1 MHz for electrodes EB, EB1, and EA; the ratio is between about 0.7 and 3.0 on average. At IS1, the resistance in 2005 was very good (69 Ω) but in 2009 the value was found to be excessive at low frequency (exceeding the capability of the low frequency measuring device) and the curve obtained at high frequency has the same trend as the other rods, with average impedance being in the same range. Furthermore, the device had difficulties to get the data at 63 kHz frequency (same as for the old simulated house) showing that the impedance is not as good as the value obtained in 2005. It is the same for the utility rod which shows the same behavior as IS1 with high value for resistance.

5 CURRENT SHARING

As explained before, we are using here the standard [7] concept of sharing i.e. the sharing of peak values of current even if not occurring at the same instant. By the way, records of current waveforms from triggered lightning experiments show that the waveshapes at various locations are very different and especially don't peak at the same time. For that reason, Rakov et al. [8] recommend charge transfer as a better quantity than the peak current for current sharing. For consistency with what is described in standards [1] and what has been measured in 2009, we use here below the sharing based on magnitude of current.

Data from the 2005 experiment indicated that the current injected at the test house into the utility cable at measuring point D was higher than that measured at the other end of the cable at the IS1 earthing point. It appears that electrical breakdown occurred both in the cable insulation and at the utility meter. A part of the current injected in D has flowed to the soil through the punctures along the cable before reaching the earthing at IS1. Having no way at this stage to determine the amount of current flowing along the cable nor to know when the cable has been punctured, the assumption will be that total lightning current is shared only between earth electrodes EA, EA1, EB, EB1, the counterpoise, the utility and IS1 rods.

Since EA1 impedance was not measured in 2009, we will assume that EA1 is similar to EB1 in construction. As shown in Figure 6, the initial arrangement of 2004 had a pair of interconnected rods at each of the two opposite corners of the building at locations EA and EB. In 2005 the outer rods were disconnected at EA and EB and rods of the same type and size were added at locations EA1 and EB1. All these rods and the utility rods were interconnected by the counterpoise.

The average impedance measured in 2009 at rod EA, EB and EB1 ranged between 405 Ω and 443 Ω. The average impedance at utility rod had a higher value of 593 Ω. Average impedance measured at IS1 was 467 Ω. As expected, the lowest average impedance was measured at the launch tower earthing system with a value of 349 Ω.

Table 3 presents the calculated current sharing based on average impedances measured in 2009. The percentage of current flowing through each of the measured location is inversely proportional to its average impedance.

This table also contains average currents measured on down conductors during the 8 strokes recorded in 2005 (0510-1, 0512-1, 0512-2, 0514-1, 0517-1, 0517-2, 0520-1, and 0521-1) as given in [3].

To make comparable the results from the 2005 experiments and 2009 measurements, we had to determine the portion of current in each of the earthing rods. However, the current in the rods were not measured in 2005 except for IS1 and instead only the current in down conductors above the earthing rods were measured.

We assumed here that since the lightning current was being injected in the middle of the structure, the sharing of current measured in down conductors would be the image of the impedance of the earthing rods connected below. For this assumption to be valid, it must also be assumed that the current in the utility rod is negligible compared to the other rods (the 2004 experiment showed that current in the utility rod was low and measurements in 2009 show that this rod exhibited the worst impedance of all other earthing electrodes). It is likely that a significant current flowed to ground via the counterpoise but we ignored this current here.

A more complex model, taking into account the impedance of the counterpoise and the 50 m cable to IS1 may be used to try to better approximate the sharing of current but the fact that more current is measured in D (injected in the cable neutral and flowing towards IS1) compared to that measured at the other end of the cable at IS1 would require the final analysis to be based on more assumptions regarding losses along the cable.

The 2005 and 2009 results match quite well except for electrode EB. The reason there is much more current measured in down conductor B than in others could be that the old test house and its earthing system are not far from the electrode at measuring point B, allowing some current to be dispersed by this additional earth electrode. This was not observed during the earthing impedance measurements made in 2009 either because the earthing system from the old test house has degraded since 2005 or because the breakdown in soil occurs only at high voltages associated with lightning currents which do not exist at the very low operating voltage of the impedance meter.

It is interesting to note that the sum of calculated currents in the utility rod at the test house and electrode EB, based on measured impedances, is 31 % of the current; which is close to what is found to be the average for measurement point B (36%) in the 2005 experiment.

This analysis does not consider the current measured at point D in the 2005 experiment for the reasons explained earlier. However, we could use IEC 62305-1 [7] to try to estimate the current sharing between the local earthing at the test house and what is injected in the utility cable and IS1. Annex E of that standard allows such a calculation, based on local earth impedance and the earthing impedance of the cable given as a function of the soil resistivity. The earthing impedance of the cable is suggested in that document to be 35 Ω, due to high soil resistivity. The local earth impedance is calculated based on 2009 measurements, taking into account all the measured locations in parallel (at EA, EB, EA1, EB1 and at the utility rod). This leads to a sharing of current of 28% in local earth and 72% in the cable. Data from the 2005 experiments give a value of 60% measured in D, so the earthing system existing in 2005 at the test house was probably more efficient to disperse high frequency currents locally than what has been measured in 2009. This was already suggested by comparison of the earth low frequency resistances between 2005 and 2009.

Table 3: Comparison between the 2005 experiment and earthing measurement made in 2009.

Electrode location	Current based on average impedance in % of injected current	Measuring point (see figure 4)	Observed average current (2005) in % of injected current
EA	18,7%	Down conductor A	19,7%
EA1	17,1%	Down conductor A1	24,0%
EB	17,9%	Down conductor B	35,9%
EB1	17,1%	Down conductor B1	20,5%
Utility rod at test house	12,8%		
IS1	16,3%	Cable neutral earthing connection at IS1	17,1%
Total	100,0%		

Reference [4] raises a question: "The apparently poorer LPS performance in 2005, compared to 2004, seems to be inconsistent with the notion that a buried loop conductor (employed in 2005) represents a superior grounding system relative to short radials (employed in 2004). The reason for this unexpected result is presently unknown." The low frequency values for the resistance measured in 2004 and 2005 show exactly the same trend. The value in 2004 was better than in 2005. This could be related to different moisture content in the soil or bad contact between the electrode and soil due to excavation around the building during the installation of the ground ring electrode. Based on experience with the earthing impedance measuring device in various soils and also based on previous tests at Camp Blanding [8], we can assume that at high frequency the vertical rods behave like a capacitance while buried horizontal conductors behave like inductances. The ground rods are then a better path than the buried conductors for the higher frequency components of the current. Thus, the loop should exhibit an inductive behavior compared to the pair of interconnected earthing rods used in 2004; which should exhibit a predominantly capacitive behavior. At low frequency the rods and buried conductors have high resistance values due to high soil resistivity. At high frequency, more current will be injected in the rods compared to the loop. The data indicate the two ends of the building exhibit different resistances to ground; better in the south part than in the north. In 2004, the current was injected near electrode A while in 2005 current injection was in the middle of the lightning protection system. At high frequency in 2004, more of the current should have been injected in rods EA (lower resistance and also nearer the injection point on roof) and a smaller part in rod EB, separated from electrode EA by an inductive link. At high frequency in 2005, the sharing of current with the injection point in the middle was probably better distributed amongst the various rods in inverse value of their average impedance; with limited current circulating in the buried loop counterpoise. If the soil resistivity had increased due to less moisture in the soil, the contact resistance would be greater (as observed) and the capacitive coupling probably not as good. With 2 rods involved in 2004 at EA compared to a single rod in 2005, this could explain such phenomena. Of course, such a speculative explanation needs to be studied in more detail.

6 CONCLUSIONS

High-frequency earth impedances have been measured in 2009 at Camp Blanding at various earth electrodes locations and compared to previous records obtained during triggered lightning strikes to a test house. It appears that in spite of some difficulties due to high soil resistivity (sand, low moisture content, etc.), the measurements have been successfully performed. Sharing of current among various electrodes based on the measured earth impedances matches quite well with data recorded in 2005 during triggered lightning experiments. Of course, some results are in need of further in-depth analysis. Some current was apparently flowing through punctured insulation of the utility cable and some current was dissipated by the counterpoise, both effects being not taken into account in our calculations. In addition, the quality of earthing has appeared to generally decrease between 2005 and 2009. It is advisable to try making the same impedance measurements again in a time frame and moisture conditions compatible with the conditions during direct lightning tests to be able to make more general and accurate conclusions. In spite of this, the high-frequency earthing measurements appear to be a good tool to evaluate earthing behavior under lightning conditions.

7 REFERENCES

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