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Grounding Analysis of Electrical Installation in Sub-Saharan Regions

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Abstract: For a while, research has been focusing on the grounding of electrical installations. The main focus of this research is on the behaviors of these industrial frequency grounding and steady-state grounding; in addition, the resistivity of the soil considered was generally close to 100 Ω.m (value often encountered in temperate regions). This is not the case in tropical regions in certain types of terrain (the results of the measurements carried out in the Democratic Republic of Congo prove it: the resistivity of soils can reach several thousand ohms-meters.
Keywords: Grounding, resistivity, distribution grid

I. INTRODUCTION

In addition, grounding standards are primarily based on these data, which are no longer true for resistivity for certain types of soil in a tropical environment such as sub-Saharan area. Worse, in some of these areas, the keraunic level is high.

At very high frequencies, grounding behaviors are very different from those at industrial frequency. Several theoretical and experimental studies have been carried out on this subject, but gray areas still persist to this day. Simplifying assumptions add to these gray areas and further complicate accuracy in the analysis.

Lightning discharge (unavoidable in regions with a high keraunic level), with high energy levels, coupled with poor soil characteristics (high resistivity), leads to operational difficulties and careful implementation of the earth, otherwise disturbances in electrical installations are repetitive; in addition, the safety of equipment and people is no longer guaranteed. Digital analysis tools for evaluating grounding are therefore necessary.

In this paper, we will use finite element calculations to evaluate the performance of the grounding by integrating several possible cases and configurations, in order to get closer to the physical realities. Comparisons will be made with analytical calculations, which in many cases make use of several approximations to make them simple. Concrete solutions for the best realization of grounding, minimizing resistance and step voltage, will be proposed.

Most grounding configurations require finite element calculations in three dimensions. These become expensive in terms of time and resources. A so-called "disturbance" method has been developed, which consists in subdividing the three-dimensional problem into several axisymmetric problems, the time and the resources for the calculation becoming substantially reduced. This method is detailed in the second chapter. The finite element calculation will also make it possible to analyze, again in this paper, the transient behavior of earth electrodes facing the lightning wave. The last part of this research is devoted, in the first part, to the results of these measurements. From these results, we propose concrete solutions for the best realization of grounding, respecting the standards for the safety of equipment and people.

Finally, the transient behavior will be analyzed, for cases of earth electrodes of simple form and the effect of the high resistivity of the soils on this behavior. Since cost is an important aspect in a tropical environment (generally poor), we will take it into account in the optimal solutions for grounding.

The interest of this research on the groundings is to allow their meticulous realization in order to minimize the negative impact on the harmonious functioning of the electrical networks in poor regions and of high resistivity. To do this, we must, as we have just pointed out above, get closer to the physical realities of the phenomena involved.

II. GROUNDING IN REGIONS OF HIGH SOIL RESISTIVITY IN SUB-SAHARAN COUNTRIES: PRACTICAL CASES IN THE DEMOCRATIC REPUBLIC OF CONGO

In this part of the paper, we will present the results of the measurements carried out in the Democratic Republic of Congo (Lubumbashi) for the resistance of the grounding of the distribution network and the resistivity of the grounds. From these results, we will, for concrete cases, propose solutions for the proper grounding.

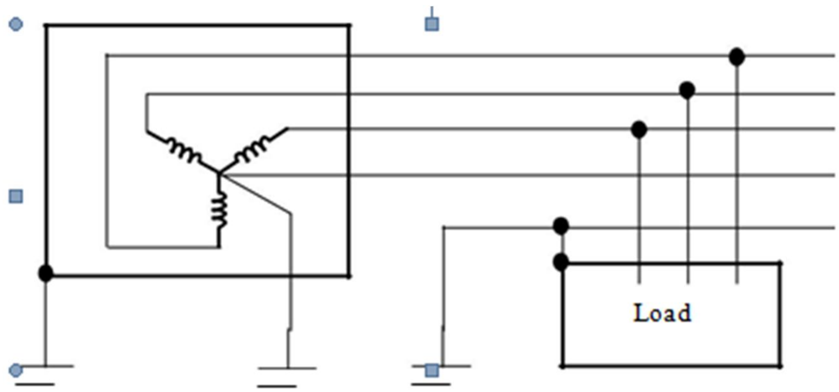
A. Measurements Of Grounding Mv / Lv Cabins Of The Distribution Network Of The City Of Lubumbashi

1) Ground Connection Schemes For Mv / Lv Cabins In Lubumbashi's Distribution Grid: The ground connection scheme adopted by national company of electricity in DR Congo for its distribution network in the city of Lubumbashi is GG (Ground-Ground) in LV. As a reminder, in this diagram, the neutral of the MV / LV transformer LV side is grounded and the masses of the electrical receivers are also grounded. With regard to MT, there are two cases:

a) The masses of the MV / LV substation (cab) are connected to the LV neutral and to the same earth electrode: this is the case of several recent 20 / 0.4 kV compact cabs. This is what network operators call single-entry cabs.

b) The masses of the MV / LV substation and the neutral are connected to earth by two separate earth connections: this is the case of several older 6.6 / 0.38 kV masonry cabins. This is what operators call separate two-land cabins (the earth of the cab masses is called earth HT and the earth of the neutral of the transformer is called earth LV). The two-earth resistors (HT and MT) must be less than 10 Ω.

MV/LV station



Cabin with two grounding connections

Station MV/BV

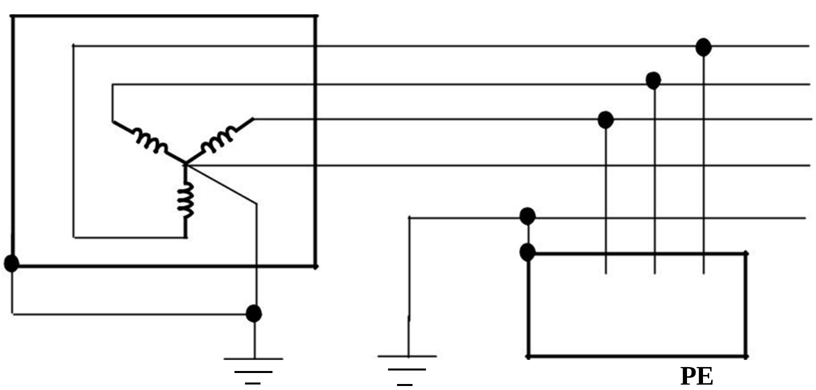


Fig.1: Ground connection schemes of the Lubumbashi distribution system cabins.

B. Grounding Standards For MV / LV Cabins In Lubumbashi's Distribution Grid

1) Depending on the voltage level, the MV / LV network of SNEL (Société Nationale d'Electricité du Congo) the national power supplier in DR Congo, has two types of cabins:

a) cabins 6.6 / 0.38 kV and

b) cabins 20 / 0.4 kV

2) Depending on the construction, there are:

a) Masonry cabins, generally with 6.6 / 0.38 kV voltage levels and relatively old construction;

b) Low post cabins, in newly electrified and non-dense neighborhoods;

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c) The Cabins high of pole;

d) Compact cabins, generally of 20 / 0.4 kV voltage level and of recent construction.

The distribution network of the city of Kinshasa has the following voltage levels: 30 kV (metered in the substations), 20 kV, 6.6 kV and 380 V (met in the distribution cabins).

3) The maximum values of the grounding resistances depend on these voltage levels. Resistances must therefore be:

MV ground (30 kV, 20 kV and 6.6 kV) and LV (380 V) separated:

a) Ground MV: R <10 Ω

b) Ground LV: R <10 Ω

MV and LV lands connected (single earth): R <1 Ω.

The resistance of a network of ground varies with the seasons. We therefore found it important to carry out two measurement campaigns (one during the rainy season and the other during the dry season of 2017).

C. Measurement Results

The measurements of the resistances were carried out with the ground meter GEOHM C which makes use of the method of fall of potential presented in the presentation. This unit operates at a frequency of 125 Hz, to avoid interference with potential 50 Hz stray currents.

Fig. 2: *Ground tester GEOHM C.*

The detailed results are presented in the following table and graphs.

Table 1: Measurement results related to the standard.

standard	Rainy season								Dry season							
	Ground only		Ground separate				Total		Ground Only		Ground separate				Total	
			Ground HV		Ground MV						Ground HV		Ground LV			
	N°	%	Nbr	%	Nbr	%	Nbr	%	Nbr	%	Nbr	%	Nbr	%	Nbr	%
Yes	0	0	7	66	8	90	18	54	0	0	7	67	6	75	12	50
Not	11	100	5	34	2	10	15	46	7	100	2	33	2	25	12	50
Total	11	100	12	100	10	100	33	100	7	100	9	100	8	100	24	100

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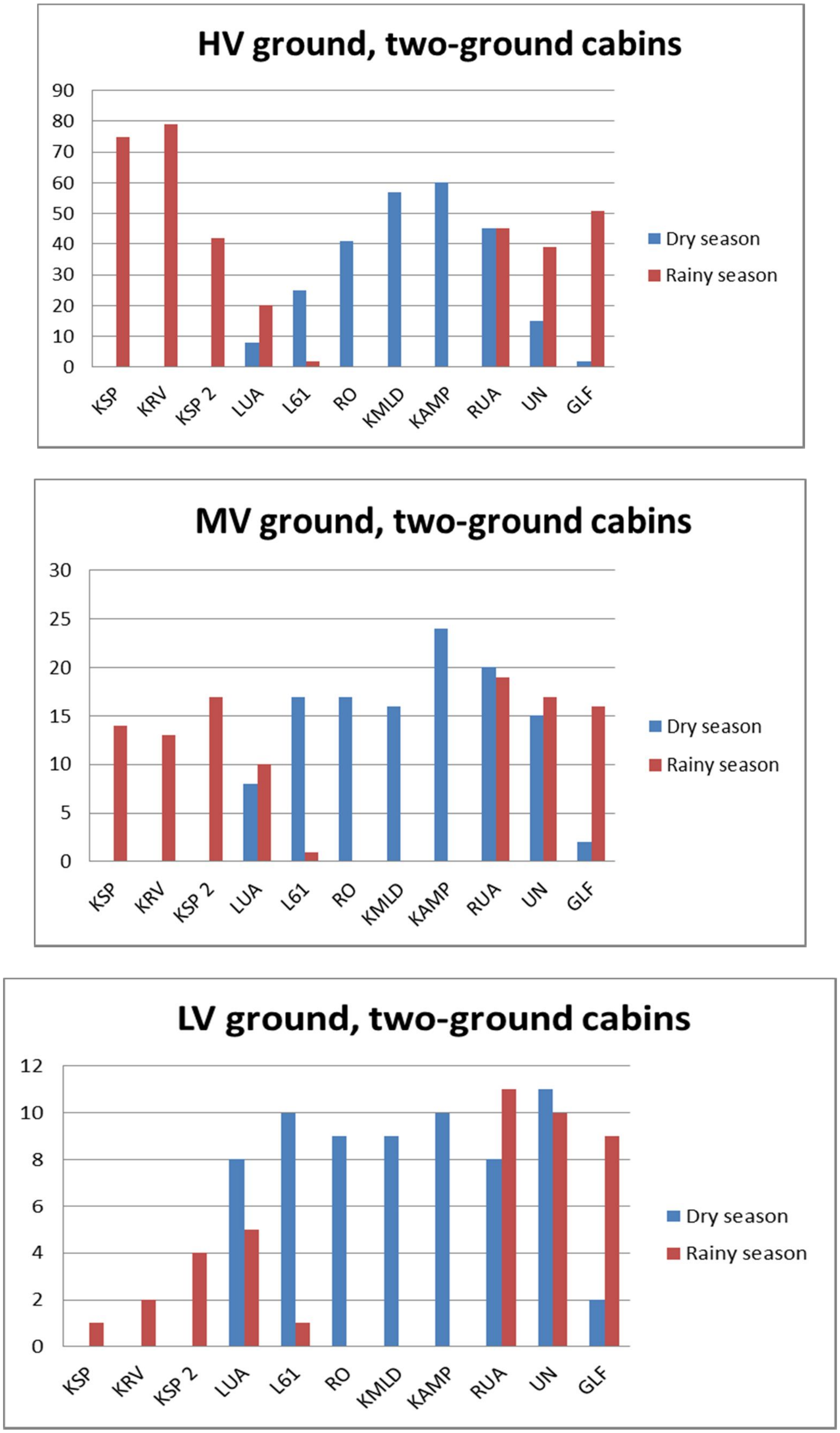

Fig.3: Ground resistance statistics for MV / LV cabs of the Lubumbashi grid (DRC).

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III. MEASUREMENT OF SOIL RESISTIVITY

A. Soil Structure Of The City Of Lubumbashi

The soils of the city of Lubumbashi are subdivided into tree main below:

1) The soil is a laterite which is of the clay type.
2) Between 0.6 and 1.5. So, we are in the presence of a Limon layer. For the geotechnical, silt refers to an intermediate granulometric fraction between clay and sand, that is to say the particle size fraction 2 µm-20 µm and, by extension, a soil family where this fraction predominates.
3) In the third layer the different penetrations on our site, we see that we are in a material with high resistance to the tip, like a healthy rock, a compact sand; because resistance to tip has increased significantly for a small depth.

For resistivity measurements, we chose the dry season because it corresponds to the highest resistivity of the soils. We used the GEOHM C which uses the four-electrode method. Two measurements of the resistivity were carried out during the rainy season at Kasangiri, whose soil is of type I and on the UNILU Campus. The results are given in the following figures:

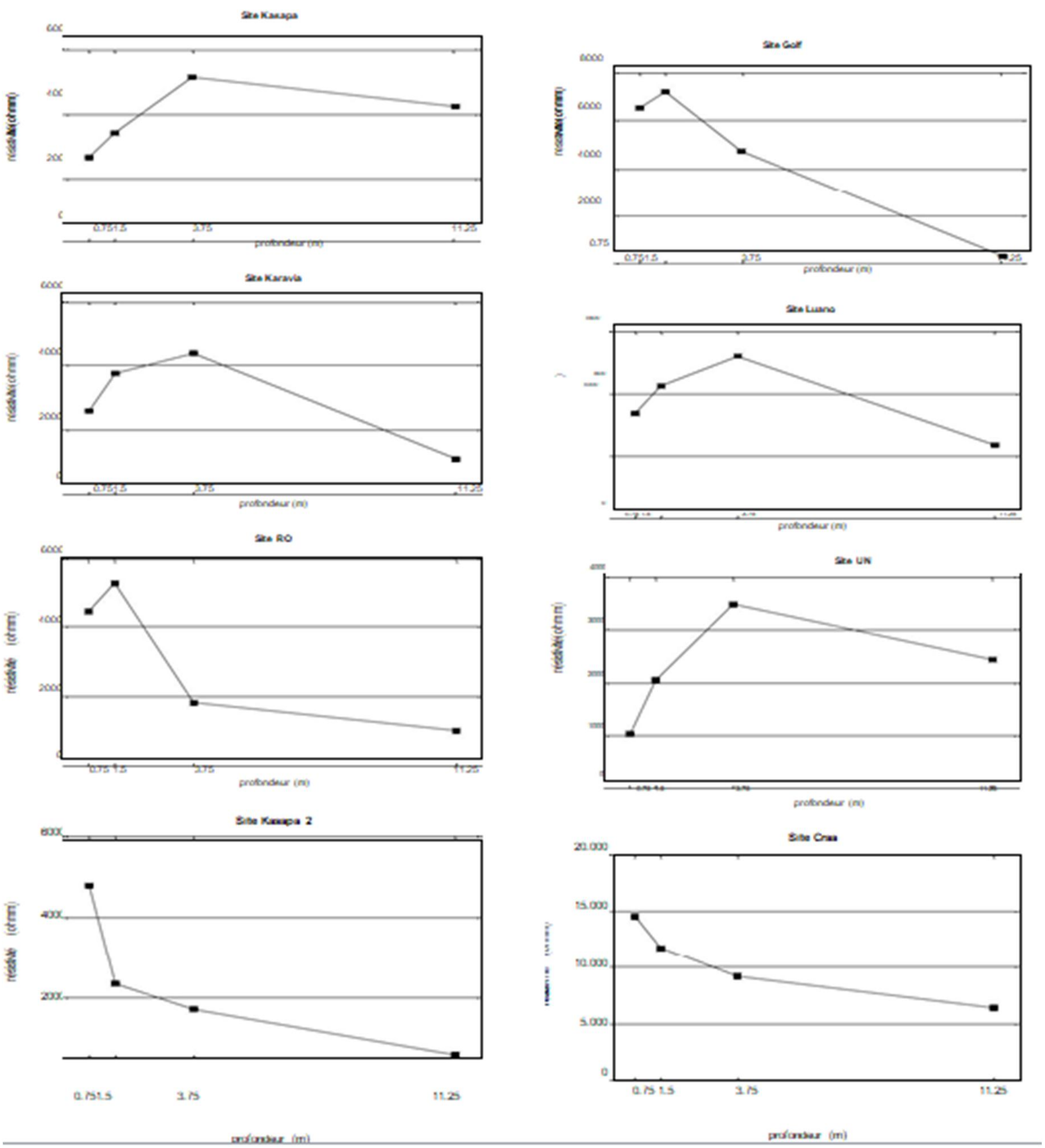

Fig 4: Resistivity of some sites in the city of Lubumbashi, dry season

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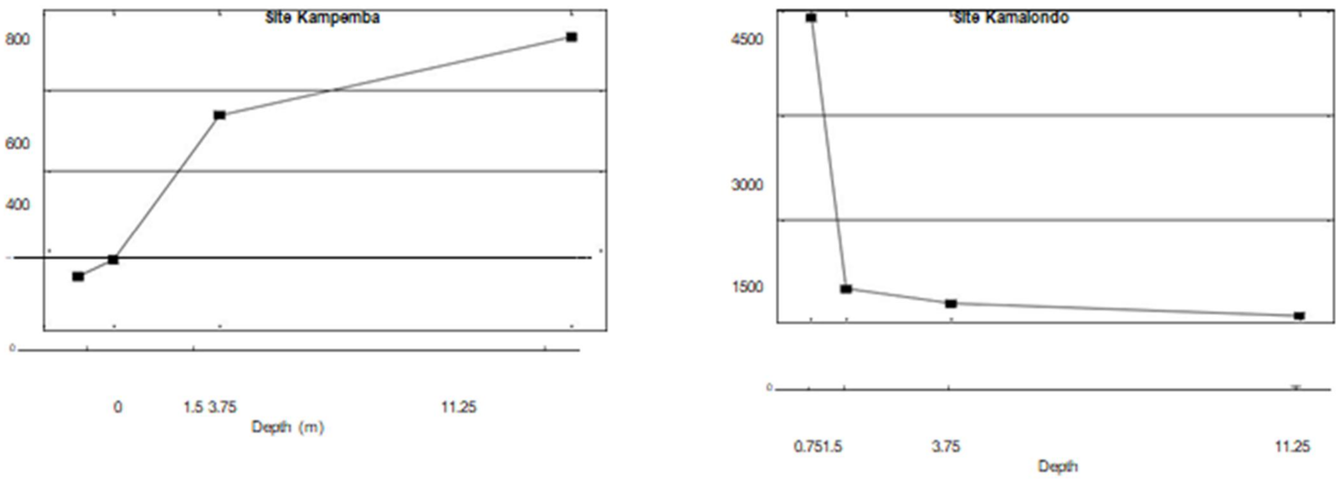

Fig.5: Resistivity of some sites of the city of Lubumbashi rainy season.

The average values of the resistivity can be represented in the following figure

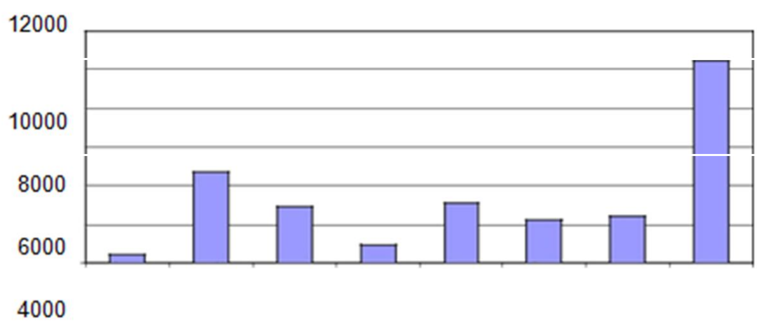

Fig.6: Average values of the resistivity of some sites of the city of Lubumbashi, dry season 2017

B. Grounding Schematics Of Mv / Lv Cabins In The Distribution Network Of The City Of Lubumbashi

In the distribution network of the city of Lubumbashi, various processes are used to achieve ground networks, depending on the types of soil. The following figures illustrate the different configurations used.

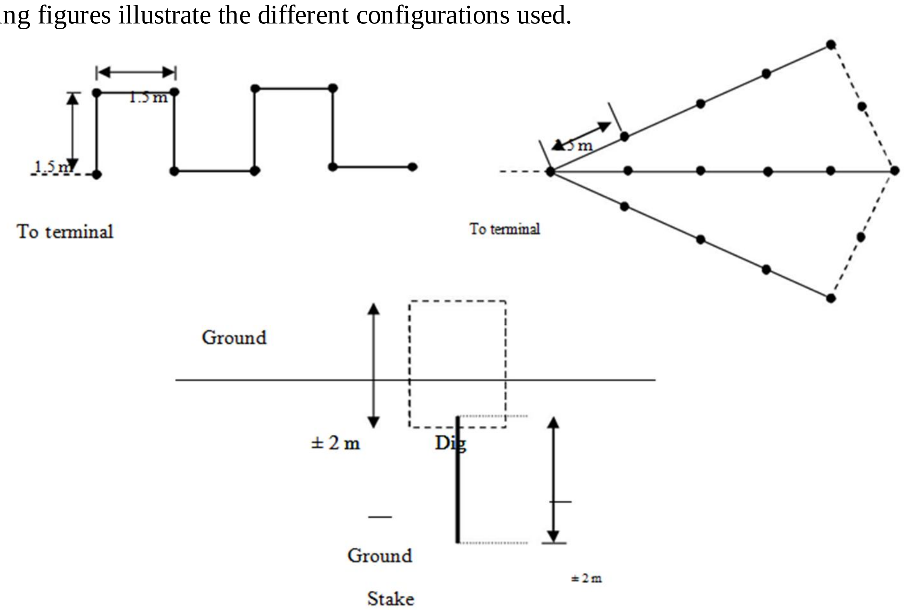

Fig.7. Different grounding configurations MV / LV cabs.

C. Observations Related To The Measurements And Grounding Scheme On The Lubumbashi Distribution Network

Examining the results of the measurements and the grounding scheme presented above, it emerges as follows:

1) The values of the MV / LV cab resistances are roughly doubled when changing season, which makes it impossible to draw conclusions with rainy season measurements only.
2) In the rainy season as in the dry season, all single shore cabins are out of the ordinary, most cabins have resistances varying between 1 and 2 Ω.
3) Separate ground cabs have earth resistance values for most standards.
4) The value of the grounding resistance of the Gaya cab is higher in the rainy season than in the dry season.
5) Some land values are very dangerous and do not ensure the safety of people and installations (case of Karavia cabins, with 3500 Ω HT side in dry season, Kasapa, with 37 Ω HT side in rainy season and Luano 2 , with 72 Ω HT side in dry season). It should be noted that these cabins are also very disturbed in their operation.
6) The values of soil resistivity are, in some places, very high and exceed 10 k Ωm (measured at the campus substation), especially in height and in places where the soil is sandy.
7) No average resistivity value is less than 350 Ω.m, even in swampy terrain.
8) In Karavia, the resistivity is increasing with the depth; this is explained by the presence of the rock in the ground in depth. This land abounds besides the quarries of the city of Lubumbashi.
9) The newly installed groundings have almost equal resistance in the rainy season and in the dry season: this can be explained by the fact that the salt used by the technicians to improve the local conductivity of the soil around the electrodes still acts (wireless cabin case).
10) No measure of the resistivity of the ground is realized before the grounding due to lack of devices. And even the measurement of the resistance of the groundings is not reliable because the apparatus used is not efficient and precise because it makes use of the method of the three points [Electricité de France, Direction of studies and researches, 1984].
11) The grounding scheme does not respect the recommended distance between the electrodes (1.5 m instead of a distance greater than the length of the electrode), which does not allow the electrodes to be considered independent each other.
12) Subscriber installations are not systematically controlled and many of them use the earth as a return conductor (neutral) and sometimes lack grounding. The GG grounding scheme imposes a grounding resistance on the DDR threshold dependent subscriber. No constraints making the use of DDR compulsory exist on the distribution network of the city of Lubumbashi. The protection of persons against indirect contact is not, in this case, adequately ensured in residential electrical installations.

D. Improved Resistance Of A Grounding

1) *Introduction:* In regions of high resistivity of the ground, the usual grounding configurations do not allow to obtain resistances and / or relatively low impedances, and thus respecting the standards. It is then necessary to find effective means to reduce these resistances (impedances). Finite element resistance calculations are of paramount importance because they allow us to quantitatively evaluate the substantial improvements in grounding. Many solutions exist, but we will have to choose those that minimize the cost of installations, while respecting the standards. In the following paragraphs, we will list these different ways and evaluate the impact of the improvement of the resistance of the grounding that they allow.

E. Increased Electrode Length

For a resistivity = 100 Ω.m and, for different analytical relations, the resistance of a cylindrical ground rod of radius r = 0.0125 m depending on its length. Doubling the length of the electrode reduces the resistance by only 45% in homogeneous soil. It should be noted that this statement rarely exists in practice. Measurements are therefore necessary [G. Vijayaraghavan, Mark Brown, Malcolm Barnes, 2004].

In addition, the increase in the length induces the increase of the inductance of the stake, so its impedance, which is bad for the high frequency currents.

F. Increased number of electrodes

The resistance of a ground can be reduced by increasing the number of electrodes. The literature indicates that increasing the number of electrodes decreases resistance but not an inverse factor [G. Vijayaraghavan, Mark Brown, Malcolm Barnes, 2004]. The following figure gives the resistance as a function of the number of cylindrical electrodes for a straight line configuration and for a distance between electrodes equal to twice the length of the electrodes, ie l = 2 m, d = 4 m, r = 0.0125 m and = 100 Ω.m.

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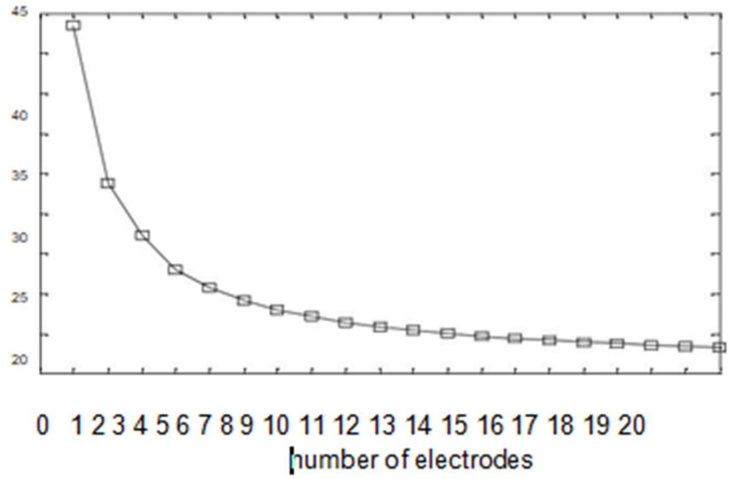

Fig. 8: Resistance according to the number of cylindrical electrodes

This figure shows the impact of the increase in the number of electrodes. For example, going from one to 20 electrodes, the resistance is divided by 10, as previously emphasized. The best reduction in resistance occurs when going from one to two electrodes. As the number of electrodes is increased, the reduction in resistance becomes smaller. This means is the most used to obtain a reduced grounding resistance. It requires, however, space and increases the cost of grounding.

G. Increase Of The Distance Between Electrodes

The figure below shows the resistance of two electrodes, three electrodes aligned and at the vertices of an equilateral triangle, and four aligned cylindrical electrodes at the vertices of a square (r = 0.0125 m, l = 2 m) respectively. The distance between them, for a homogeneous soil (ρ = 100 Ω.m).

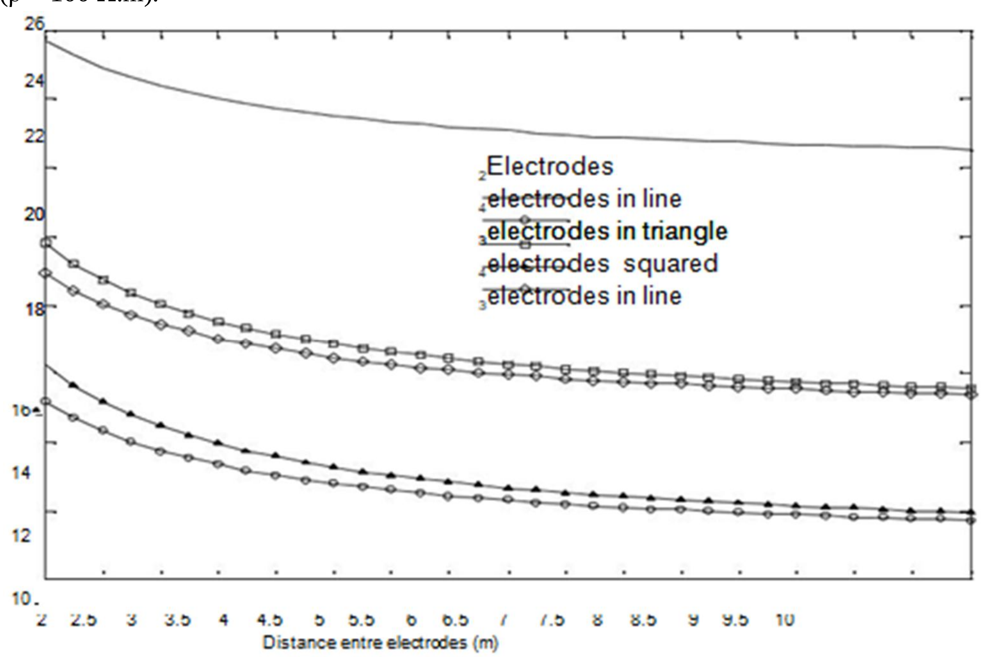

Fig.9: Resistance as a function of the distance between the cylindrical electrodes.

We note well that for distances between electrodes just greater than the length of this one, the reduction of the resistance of the stakes is quite sensitive and decreases with the increase of the distance (for example, for 3 electrodes at the top of a equilateral triangle, the resistance is decreased by 13% when the distance increases from 2 m to 3 m, whereas when it goes from 2 m to 10 m, the reduction is only 21%). [Vijayaraghavan G., Mark Brown, Malcolm Barnes, 2004].

H. Increased Electrode Diameter

This is a vertical copper electrode 2 m long, in a ground of 100 Ω.m. The resistance of the grounding according to the diameter of the electrode for several configurations by applying the relation of Dwight-Sunde is given in the following figure:

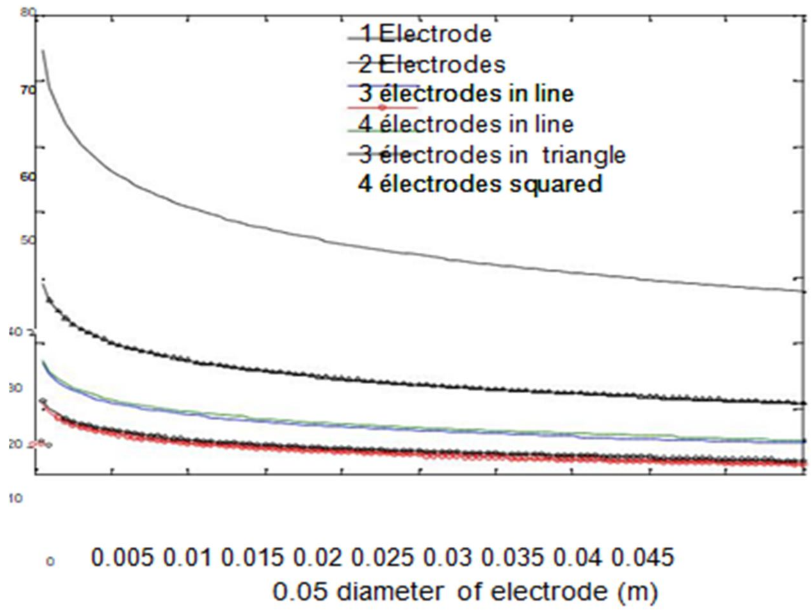

Fig. 10. Resistance as a function of the diameter of the vertical cylindrical electrode.

For a ground rod buried in a resistivity ground of 1000 Ω.m, surrounded by a layer of cylindrical charcoal of resistivity 10 Ω.m, the table below gives, for a vertical electrode of length 2 m and 0.0125 m radius, the grounding resistance according to the radius of the charcoal layer. The resistance of this stake without the charcoal layer using the Dwight-Sunde relation is 434.61 Ω.

The figures below show the potential distribution (in V) and the current density (in A / m^2) in the soil for a cylindrical post (l = 1 m, r = 0.0125) in a supposedly homogeneous soil (ρ = 1000 Ω.m), surrounded by a layer of low resistivity material (r_m = 0.5 m, ρ_m = 10 Ω.m) for a current.

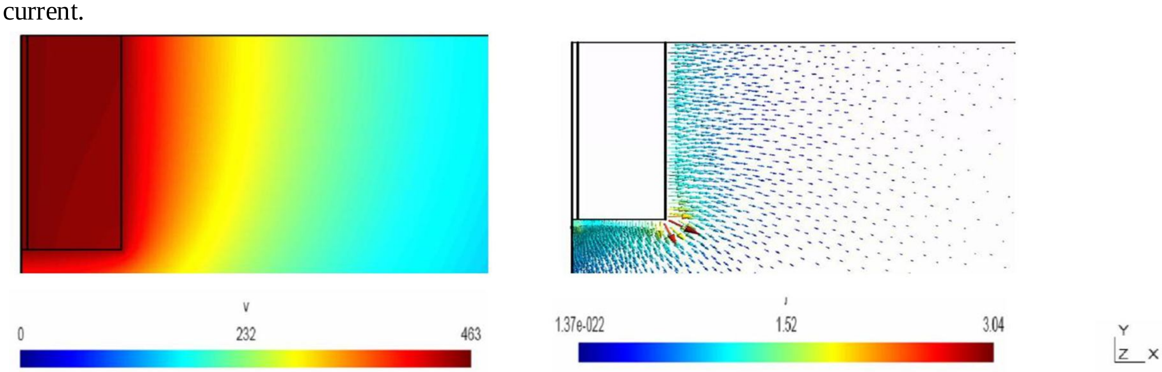

Fig.11 Potential in the soil (left) and current density (right).

I. Practical Case Of Grounding

This example shows the result of measurement and calculation of the resistance of a grounding that we had made in Lubumbashi (Democratic Republic of Congo). The pattern of implantation of the copper ground rods (number 7) is given to Diagram 4. The depth of burial of the stakes is 1 m below the surface of the ground.

The earth is represented by 4 different resistivity layers measured (the results are given in Table 4below). The stakes are surrounded by a layer of charcoal of 1 d_m radius, whose resistivity is estimated at 10 Ω.m. The distance between two consecutive stakes is 4 m. In EF calculations, the influence of the horizontal cable connecting the stakes can be neglected because of the high resistivity of the surrounding ground.

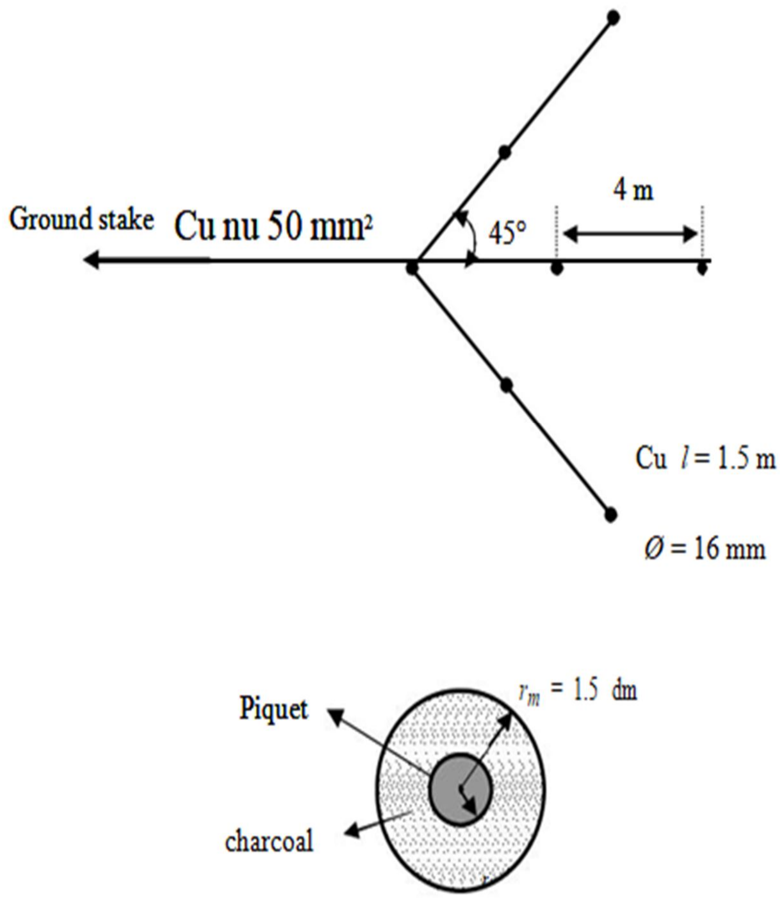

Fig.11: Geometric characteristics of the grounding.

Table 2: Resistance, multi-layered soil and homogeneous soil, with the layer of charcoal.

Resistivity (Ω.m)	ρ_1	ρ_2	ρ_3	ρ_4	ρmoy	$\rho_a = 0.5\ (\rho_{max} + \rho_{min})$
	4400	500	290	110	1325	2255
R EF (Ω)	26.97				66.42	112.71
Error (%)	12 %				177 %	367 %

These results show that the EF modeling that we have presented in this work is suitable for evaluating frequency-grounded grounding. The characteristics of the soil are well presented without any restriction. The results of the calculations and the measurements show a difference of 12%. This is probably due to the fact that we have neglected the different cables connecting the different stakes.

But since they are in the very high resistivity ground, their influence should be negligible. Considering that the soil is homogeneous, the errors are very large (177% and 367% respectively). These results prove once more that our model has no limitation as to the actual soil structure, the soil modeling in a homogeneous layer giving biased results. The following figures give the potential distribution (in V) on the surface of the ground and in the horizontal plane containing the upper ends of the stakes, for a current.

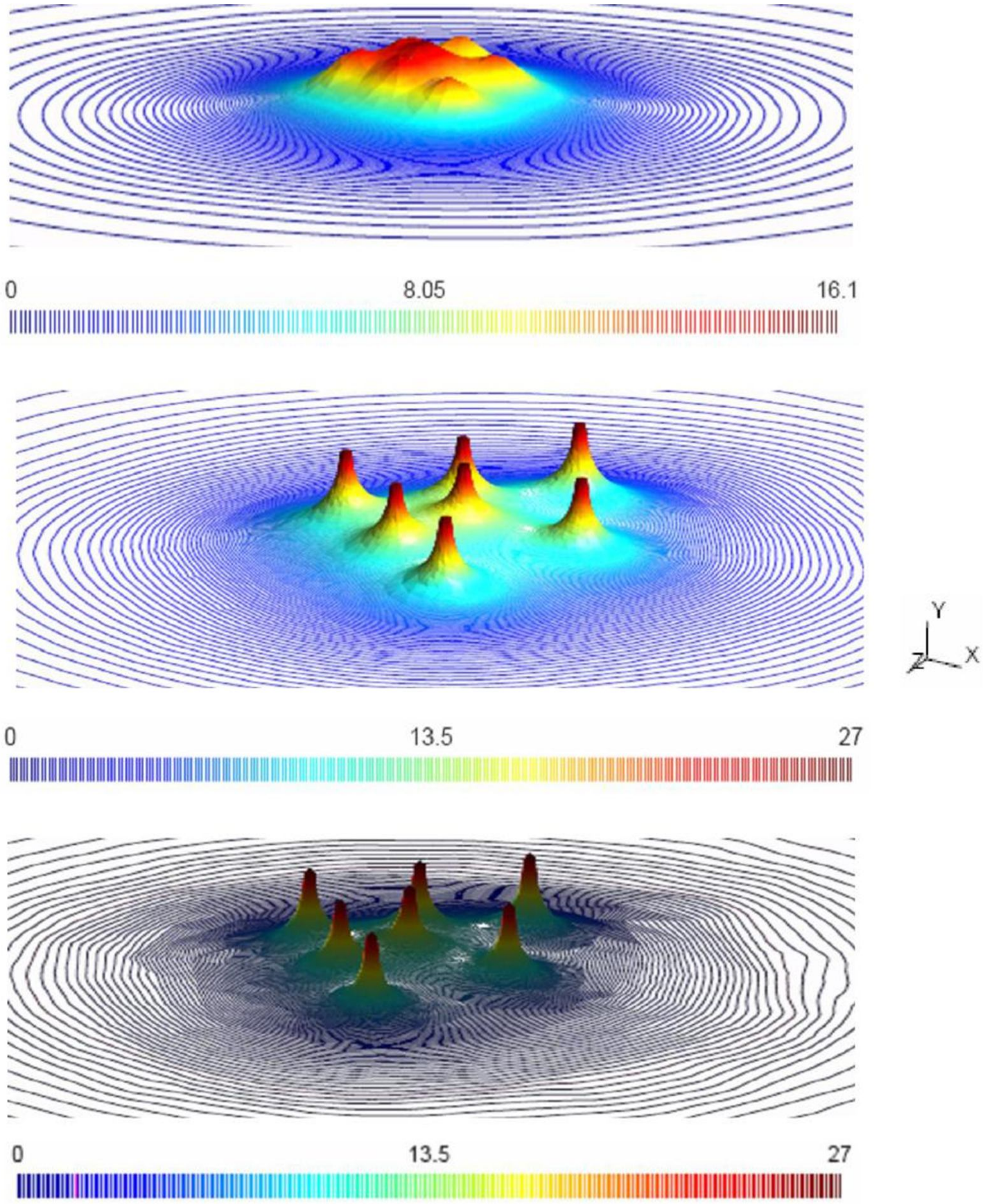

Fig. 12 Potential distribution on the ground surface y = 0 m (high), in the plane containing the upper ends of the pegs y = -1 m (middle) and in the plane containing the lower ends of the pegs y = -2.5 m (low)).

IV. GENERAL CONCLUSION

In this work, to evaluate the resistances of the grounding (also the electric field and the distribution of the potentials and the density of current) in industrial frequency, models of computation by finite elements were presented in 2D axisymmetric and in 3D, for some electrode configurations. These computation models, which have the advantage of being closer to the actual physical situation, and which apply to more complex configurations, have been validated in comparison with the analytical calculations, with relatively small and often order of 10%. These results have shown that axisymmetric calculations are much less expensive in terms of computation time and resources because they allow much finer meshes.

However, many of the actual grounding configurations must be modeled in 3D because they are not axisymmetric. Resources and calculation time are very important. The perturbation technique has made it possible to solve by finite elements, a 3D problem by subdividing it into several axisymmetric problems, by an iterative calculation, the different problems being corrected with respect to each other.

Since grounding resistance must be low and given the high values of resistivities in tropical regions, the means to reduce this resistance at lower cost are proposed. Finite element calculations also allow us to evaluate the rate of reduction of this resistance, which allows for easy grounding design. The least expensive method proposed is the addition of a low resistivity layer around the electrode. Currently, many grounding specialists make use of bentonite, but because of its cost, we offer charcoal powder. Resistance reduction rates can exceed 50% with this technique. In addition, it is also noted that for the same grounding resistance, having several vertical cylindrical stakes is much less expensive than having a few longer stakes. But it would be interesting to be able to check how the electrical conductivity of the charcoal powder behaves over time.

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