Grounding Microgrid Systems in Metropolitan and Commercial Areas

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Abstract –Adjacent-grounding systems, in metropolitan areas, are usually interfering, because moreover common external conductive parts interconnect naturally them. Their integration to constitute a grounding microgrid system GMS allows making each grounding system more extended than its ground electrode. It assists resolutely to present limited touch voltages permissible to persist longer than 10 s and so to create the conditions of an intrinsically safe grounding system ISGS. An intentional common integration of adjacent-grounding systems is admissible, because each one of the grounding systems must satisfy equal protection requirements prescribed by utilities. This paper deals with three sample cases of measurements on grounding systems in areas with high GSs density and of a large size. The tests allows identifying a grounding microgrid system assessing for each component ground electrode a dispersing capacity of the fault current more extended than its size up to the dimension of the efficiency saturation with the minimum impedance value. The identification by measures of grounding microgrid systems contribute to recognize and improve natural integrations and promote the progress of the common safety, regardless of formal validation.

Index terms - Electrical safety, grounding system, global grounding system, ground potential, zone of influence.

I. INTRODUCTION. ADEQUACY OF A GROUNDING SYSTEM TO IEC STANDARD

A ground fault current origins touch/step voltages $U_{t,s}$ within the grounding system (GS) and around its zone of influence (ZOI) [1, 2] that have not to present hazards of electric shock. Complying with the standard IEC 61936-1- EN50522 [3, 4], the conventional touch voltage limit U_L for HV a.c installations is assumed equal to U_L=80 V.
Time durations t_a of fault permanence lower than 10 s [3, 4] guaranteed by the tripping of the protective devices $t_d \leq t_a$ allow permissible limit values U_{Lt} of the touch voltages higher than U_L=80 V. The Table I show the limit touch voltage values for HV installations [3, 4].
In conclusion, it is defined a stringent correlation between the time duration of fault t_a and the permissible limit values U_{Lt} of the touch voltages. An empirical expression to evaluate the U_{Lt} in relation to the fault time durations t is the following

$$U_{Lt}=at^6-bt^5+ct^4-dt^3+et^2-ft+g \qquad (1)$$

assuming for the constants a, b, c, d, e, f, g the values shown in the Table II for times lower than 1s and higher than 1s.
The adequacy of a GS has to be verified in reference to the fault duration t_d and so to the related permissible voltage U_{Lt} and in reference to the ground fault current I_G =r I_F, being r a reduction factor of the fault current I_F.

For a tripping time t_d of the protective device, the GS is conventionally safe, if its R_G (Z_G) resistance is sized to limit the ground potential rise GPR for the fault current I_G satisfying

$$t=t_d \qquad U_G = Z_G \, r \, I_F \cong R_G \, I_G \leq F \, U_{Lt}(t) \qquad (2)$$

The factor F= U_G/U_{Lt} takes into account that the admissible values for the U_G can be higher than the $U_{t,s}$ inside the GS.
The IEC/EN approach [3, 4] generally prospects F=2. If the condition (2) is not satisfied, it is mandatory to test and provide that the touch voltages U_t inside and around the grounding system are lower than the admissible limits U_{Lt}.
It is well known that the fall-of-potential FoP method measures the ground-impedance applying a voltage U between the GS under test and a remote current probe that origins the flow of a current I_F through it. An auxiliary potential electrode is placed at various locations between current probe and the GS border, plotting the ratio of U/I_F = R as a function of probe position. The FoP provides acceptable results only if a flat portion in the potential profile has been tested very clearly and at this aim the current probe must be efficiently outside the influence of the tested GS. For a large GS or a GS in areas with high density of interfering GSs, the spacing required is normally unpractical or almost impossible. In any case, also if the measurement of the ground resistance in areas of low accessibility is unlikely; nevertheless, the assumption of the resistance R_G, as a reference parameter, plays a key role in analyzing and defining in a general way the GSs behavior.

TABLE I MAXIMUM PERMISSIBLE VALUES OF VOLTAGES U_{Lt} (t_d) ACCORDING TO THE TRIPPING TIME t_d

t_d (s)	U_{Lt} (V)	t_d (s)	U_{Lt} (V)
0.04	800.00	0.50	213.00
0.08	700.00	0.80	120.00
0.14	600.00	1.00	103.00
0.20	500.00	1.60	94.00
0.29	400.00	5.00	82.00
0.39	300.00	10.00	80.00
0.45	248.00	> 10.00	80.00

TABLE II CONSTANTS OF THE EMPIRICAL EXPRESSION (1) FOR TIMES LOWER THAN 1S AND HIGHER THAN 1S.

t [s]	a	b
≤1	7533	27451
>1 to 10	0	0

t [s]	c	d	e	f	g
≤1	38466	26581	10624	3409.8	922.3
>1 to 10	0.023	0.606	5.7945	24.432	120.64

The present trend in Europe is to operate the MV distribution with a resonant grounding system that determines fault currents in the order of 50-70 amperes and the adoption of ground fault protection-tripping times greater than 10 s.

Let us consider that it is possible to identify the GS for an assigned I_F as intrinsically safe system ISGS(I_F) [5, 6], if the touch voltage assumes values not higher than the safe values permissible to persist indeterminately or even so for a time duration higher 10 s.

In the resonant grounding systems that normally adopt a protection tripping time $t_d \geq 10s$ for the MV feeders, the GS must be an ISGS and its GPR must satisfy the condition (2) putting $U_G \leq F \, U_L$. As already noted, the IEC approach [2, 3] states in HV a. c. , the conventional touch voltage limit U_L equal to 80V and $t_L > 10s$; while it states in LV a. c., U_L equal to 50V (normal conditions) and $t_L = 5$ s.

Therefore, a general conservative definition of an ISGS has to consider the coexistence of MV-GSs and LV-GSs and to require that the R_G is equal or lower than the reference value R_{GMAX}

$$R_G \leq F \cdot U_L / r \, I_F = F \cdot 50 / r \, I_F = 100 / r \, I_F = R_{GMAX} \qquad (3)$$

Moreover, the IEC/EN standards [3,4], introduce the global grounding system (GGS) as an equivalent grounding system that ensures no dangerous touch voltages, but regardless the ground fault current I_F at which instead the ISGS(I_F) definition correlates the safety condition. A relevant limitation however to define a group of GSs as GGS is that requires formal validation by the utility, due to the contribution of the distribution cable shields, only essential for isolated GSs.

In synthesis, the GS of a MV installation has to be designed complying with the IEC criteria [3] and the parameters prescribed by the utilities for each delivery point (POD) of the MV installations:

- the prospected fault current I_F,
- the tripping times of the protective device of the utility MV feeder in reference to which size the GS and of the ground fault relay (GFR) against ground fault internal in the GS.

In this manner, the assigned tripping time of the utility's MV feeder automatically fixes the limit value $U_{Lt}(t)$ [3, 4] in relation to which the GS system of the MV installation must be sized.

For resonant grounding system, the typical tripping time value is $t_d > 10$ s that delimit the permissible voltage to $U_{Lt} = U_L = 80V$. The utility generally requires the adoption of a directional protection of the same POD by a ground fault relay (GFR) against ground fault internal to the GS. In particular the utility imposes to calibrate the tripping time of the GFR to a maximum value of the order of $t_{GFR} = 0.45s$ that is correlated to a permissible voltage $U_{Lt} = 248$ V. The resonant grounding system guarantees a fault current of no more than 50-70 A differently from the previous management of the ungrounded neutral system with a fault current of hundreds amps. This option modifies the safety conditions of the grounding systems with the advantage of reducing the value of the fault current to 50-70 A, but with the change that the utility operates the MV system with protection times greater than 10s.

It has to be noted that in case of fault in the utility network the prospected duration of the GPR can be higher than t>10 s, because in case of a fault internal to the GS the prescribed ground fault relay trips in 0.45s.

II. GLOBAL AND INTRINSICALLY SAFE GROUNDING SYSTEMS. GROUNDING MICROGRID SYSTEMS.

The metropolitan and commercial areas present a high density of MV/LV transformer power stations.

In these areas, the grounding systems are rarely isolated, but they are close to each other in their zones of influence and are interfering, interconnected or integrated.

In fact, it becomes very rare to have an area around a GS with sufficient accessibility, but in its ZOI others GSs or, generically, extraneous conductive parts ExCPs are present [5]. Generally, not buried conductors interconnect each GS to other GSs and buried conductors (intentional or unintentional) integrate them.

The interconnection and integration of GSs allow creating the conditions of an intrinsically safe grounding system (ISGS) [5, 6, 7]. Therefore, it is peaceful to suggest a free organization of adjacent GSs in an integrated GS toward the constitution of a unique grounding system as a grounding microgrid system (GMS).

A relevant aspect is that the measured value of the resistance of a GS, interconnected or integrated with other GSs, presents a sensitive reduction in comparison to the resistance value calculated in the condition of isolated GS. A significant issue is the difference in the resistance reduction between GSs isolated and interconnected by the distribution cable shields and GSs adjacent and integrated. In fact, the linear interconnection introduces series resistances R_S less negligible that increase with the distance from the ground fault point and saturate the contribution to disperse the fault current (Figure 1).

Figure 2 shows graphically the sample behavior of isolated N GSs, in a loop configuration, with independent zones of
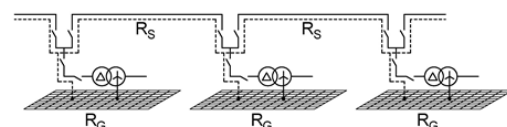

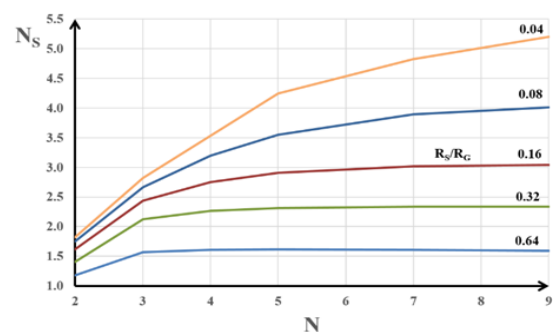Figure 1 . The scheme of a linear interconnection of N GSs.

Figure. 2. A series of R_S/R_G curves for the N-N_s in the case study of GSs assuming an equal value for R_S and R_G [8]

influence, an equal R_G value of the ground resistances and characterized by a same resistance ratio of the interconnections R_S/R_G. The series of R_S/R_G curves on the N-N_s show as the series R_S resistances saturate the number N of GSs to a maximum number N_s efficacious to disperse also increasing the number $N>N_s$ of the interconnected GSs [6].

The integration of adjacent GSs in a meshed common GS makes slight the saturation, favoring a larger partition of the ground fault current via conductors with a lower localized density of dispersion to ground. An increased integration in a larger extension tends to convert the single GSs into a GMS and reduces the common ground resistance rather than the amount of leakage current on the single GS (so, it has to be assumed $r=1$). A start point of saturation of efficiency of GMS in reducing its impedance R_{Gsps} regardless its extension has to be expected when the same impedance seen from the fault point assumes values lower than $R_{Gsps}= 0.5 \ \Omega$. At this low value, the resistance/impedance may have an appreciable reactive component [8] and the self-impedance of electrode conductors becomes not negligible.

A threshold minimum value of the impedance R_{Gmin} of a large GS or a GMS, due to the efficiency saturation to disperse the fault current, could be assumed of the order of $R_{Gmin}=0.1 \ \Omega$.

This behavior promotes the integration as a safety solution for metropolitan and commercial areas in the aim to reach the condition of intrinsically safe grounding system – ISGS $R_G<R_{GMAX}$.

Let us note that the integration over its extension even beyond the size of the saturation is able to guarantee everywhere the minimum threshold value of the impedance R_{Gmin} seen from the fault point.

In metropolitan or commercial areas, extended ISGSs can become grounding microgrid system, a public "grounding service" organized and managed similarly to the water, gas, energy, telephone or internet services.

III. GROUNDING MICROGRID SYSTEMS IN METROPOLITAN AND COMMERCIAL AREAS: INTRINSICALLY SAFE GROUNDING SYSTEMS [9, 10]

In areas with reduced accessibility, the contiguity of GSs enables their meshed integration with intentional buried conductors to form a GMS, already naturally integrated. This integrated system reduces the global resistance R_G and therefore each GS component can reach easier the safety conditions required for its adequacy.

Let us note that each GS, inside a common area, has to comply with the same safety conditions imposed at the POD of its power system. Therefore, each one of these GSs can be assumed satisfying identical protection requirements and so equally adequate to be protected against internal MV ground faults in relation to the trip time of the ground fault relay (GFR).

In other words, the integration between contiguous grounding systems is bound to the fact that each one is equipped with a directional ground relay with the same settings imposed by the distributor. In this case, the advantage that users achieve is that the internal ground faults guarantee $U_G \leq F \ U_L$ for the tripping time of the GFR (= 0.45 s), enhancing the general safety.

Therefore, all the energized power systems that can integrate their GSs are in condition of safety parity and the integration of adjacent GSs in a grounding microgrid system GMS is surely an efficient solution to satisfy the safety condition $U_G \leq FU_L$ (=cautiously F 50V). Considering that the promotion of the resonant grounding system in metropolitan areas facilitates the achievement of an ISGS condition ($I_F \leq 70A$), an integrated grounding system has to be promoted, organized and managed. In reality, there are no reasons impeding the utilities cannot promote and participate in the constitution of the GMS that tests confirm their natural existence. The connection of the shields of the utility power cables to the GS, required by the IEC/EN standards [3, 4], improves the integration of each GS, but transfers from the network to the GS external faults protected in a time higher than 10s, because the ground fault relay of the same GS cannot protect.

Then, a GS or its integrated GMS must have a constitution and an efficient dispersing area sufficient to satisfy, for an assigned soil resistivity, the intrinsic safety condition that can be characterized by a minimum diameter D_{min} of an equivalent circle. On the other hand, in zones with a high density of GSs, a large GS or the integrated GMS can reach such dimensions and an equivalent diameter D not only higher than the D_{min}, but also exceeding the characteristic maximum diameter D_{MAX}, that saturates the efficiency in dispersing the fault current.

A rule of thumb [4] to evaluate the diameter D of a circle with the area equivalent to a meshed ground electrode of resistance R_G, it can be adopted the formula

$$R_G = \rho /2D \qquad (4)$$

being the soil resistivity ρ.

Therefore, the necessary minimum prospected diameter D_{min} of the equivalent area that the single GS or the integrated GMS must occupy for the fulfilment of the intrinsic safety condition ($U_{GMAX}= F \ U_L= 100V$), can be achieved in reference to the maximum admissible value of resistance R_{GMAX} defined by the formula (3)

$$R_{GMAX} = \rho /2D_{min} = 100/r \ I_F \qquad (5)$$

D_{min} is obtained as:

$$D_{min} = (\rho /100 \cdot r) \ I_F/2 \qquad (6)$$

Let us note that, assuming for a GMS reasonably $r=1$, in reference to a soil resistivity $\rho= 100 \ \Omega m$, the value in meters of the diameter D_{min} of the GS is equal to the half value of the I_F. The diameter D_{min} will vary proportionally to the ratio $\rho/100$ of the soil resistivity and to the ratio $1/r$ for $r<1$.

Then, two other threshold values characterize a large GS and a GMS, the diameter D_{spes} and the diameter D_{MAX} related respectively to the impedance $R_{Gspes}=0.5 \ \Omega$, start point of efficiency saturation and to the minimum impedance R_{Gmin} assumed in an indicative way of the order of $R_{Gmin}=0.1\Omega$:

$$D_{spes} = \rho /2*0.5 =|\rho| \qquad (7)$$

$$D_{MAX} \approx \rho /2*0.1 = 5|\rho| \qquad (8)$$

Let us note that the value in meters of the diameter D_{spes} of the GS is equal to the value of the soil resistivity ρ. Whereas, the value in meters of the diameter D_{MAX} of the maximum area efficient to disperse the fault current of the GMS around the fault point is roughly of the order of five times the value $|\rho|$ of the soil resistivity.

Tests can identify a grounding microgrid system that does not need the validation as a global grounding system avoiding the technical and formal difficulties that the utilities usually present to do it. The identification in fact is confirmed when the measured value of the resistance of a GS diverges significantly from the calculated value due to the integration among the GSs of the GMS [8].

The availability of a detailed map of the GS that shows its configuration, any extraneous conductive parts and other adjacent GSs contributes to identify their integrated condition of a GMS. Its presumable impedance can reach the saturated minimum value R_{Gmin}, if the global extension is comparable with an area of diameter D_{MAX} in meter of the order of 4-5 times the $|\rho|$ value.

No standard prohibits improving the integration of adjacent grounding systems and therefore naturally interacting by means of metallic buried structures and common ground wires. In metropolitan and commercial areas with reduced accessibility, in a general agreement, the same utility will do well to promote technically and formally the GMS as ISGS equivalent to a global grounding system prefigured by the same IEC standard, overcoming the problem of validating the same GGS.

IV. SAMPLE CASES OF GMS IDENTIFICATION

This paper presents three sample cases of experimental measurements on grounding systems that verify the achievement of the intrinsic safety condition related to the I_F ($D_{min}(I_F/2)$, more easily when the MV distribution operates with a resonant grounding system, but also the accomplishment of the minimum efficient impedance of the order of 0.1 Ω in GMSs or large GSs. The second and third cases present a low resistivity ρ and so a related low value of D_{MAX} (≈ 4 or $5 |\rho|$) easier to reach.

A. First sample case

The GS of the first sample case is related to a building in an urban area adjacent to many other GSs. It is composed of 8 copper-plated steel rods with diameter d = 0.02 m and length h = 1.5m, connected to each other by a ring electrode constituted of a bare copper conductor (50mm^2 d=0,008m) buried in the ground at a depth of 0.5 m (Figure 3).

The GS is located, in the basement, in the interspace surrounding the building. Some structures (stairs) and the incoming pipes - gas - water, the shields of the network connecting cable are joined to the GS.

The rods are located in the 4 corners of the basement of the building and 2 rods on each one of the longer sides. The grounding system therefore has the same rectangular shape of the building with the sizes a, b long a = 60m and wide b = 25m.
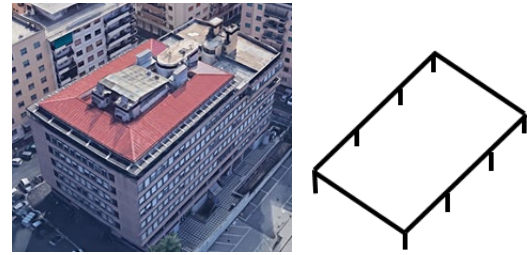

Figure 3. Sample case of GS of a building rising in a metropolitan area: the ground electrode is constituted by a ring and eight rods

The soil resistivity was measured as ρ = 66.6 Ω/m and the measurement conditions were clear weather with slightly damp soil. The prospected value of the ground resistance can be estimated by calculating the parallel of the two contributions of the ring ground electrode and of the eight rods.

The contribution of the ring electrode can be calculated [4] with the following simplified formulas

$$R_{G,ring}=\frac{\rho}{\pi^2 D}\ln\frac{2\pi D}{d}=1.33 \ \Omega \qquad (9)$$

where

$$D= \frac{2(a+b)}{\pi}= 54.11 \text{ m} \qquad (10)$$

The contribution of the eight- rods can be calculated [4] with the simplified formulas

$$R_{rod}=(\frac{\rho}{2\pi h}\ln\frac{4h}{d})/8=40.3 \ \Omega \qquad (11)$$

and

$$R_{rods}= R_{rod} / 8 = 5.04 \ \Omega \qquad (12)$$

Therefore, the prospected global resistance R_{Gp} remains estimated by the parallel of the two contributions R_{ring} and R_{rods} and therefore equal to

$$R_{Gp}=1/[(1/R_{ring})+(1/R_{rods})] = 1.05 \ \Omega \quad (13)$$

Therefore, adopting the (4), the prospected diameter D_p of the circle equivalent to the area of the grounding system is

$$D_p= \rho/2 \ R_G = 32 \text{ m} \qquad (14)$$

Let us note that the D_p satisfies the intrinsic safety condition (6) also for $I_G=I_F=70$ A and r=1 (D_p=32 m > D_{min} = (66.6/100)*70/2) = 23.1m). To measure the ground resistance with the FoP method, the current probe was positioned at 70 m from the border of the GS and therefore at more than one and a half times the D_p of the equivalent circle.

The measurements have been made by adopting the potential probe (0.2 m) at a step of 5 m, less than 1/10 of the distance between the current probe and the ground electrode under test. As in other measurement cases in areas with a high density of buildings, moving the probe away from the GS under test, the measurement of the resistance shows a slight decay of the value

Figure 4. The measurement on a GS in high-density area of buildings can identify its membership to a GMS: the two circles D_p=32 m and D_{mes} =256 m show the equivalent areas of the sample case of ground electrode related to the resistance calculated and measured respectively

without a clear inflection in the potential profile. The ground resistance value measured with the voltage probe at 40, 45, 50 m was 0.11 Ω, at 55 m it was 0.12 Ω and at 60 m and 65 m it was R_{Gmes} = 0.13 Ω.

Therefore, the considerable difference of about 8 times, between the prospected value R_{Gp} = 1.05 Ω of the ground resistance and that measured R_{Gmes} = 0.13 Ω, displays that there are other connections with neighboring ground systems.

Considering therefore that the complex of ground systems of the interfering buildings can be configured as an overall meshed system GS, the measured value R_{Gmes} = 0.13 Ω, suggests that this grounding system could be equivalent to a circle of diameter

$$D_{mes} = \rho/2\ R_{Gmes} = 256\ m \qquad (15)$$

which actually includes the presence of ground installations of adjacent buildings (Figure 4), near to the D_{MAX}.

B. Second sample case

The GS of the second sample case is related to many adjacent PV blocks inside a park (Figure 5). The GS of each block is composed of a ring electrode constituted of a bare copper conductor buried in the ground at a depth of 0.5 m with a quasi-rectangular shape with the sizes a, b long about a = 200m and wide about b = 100 m. The PV modules inside the block are grounded and interconnected to make meshed the block GS.

The soil resistivity was measured as ρ = 20 Ω/m and the measurement conditions were clear weather.

The prospected value of the ground resistance R_{Gp} of each block GS can be estimated by calculating the GS diameter analogously to the (8)

$$D = \frac{2(a+b)}{\pi} = 190.98\ m \qquad (16)$$

and adopting the (4)

$$R_{Gp} = \rho\ /2D = 20/2*190.98 = 0.05\ \Omega \qquad (17)$$

The GSs of the blocks are interconnected and so two kinds of masurement are made on each GS of the block under test with and without the connection to the other GSs. The ground
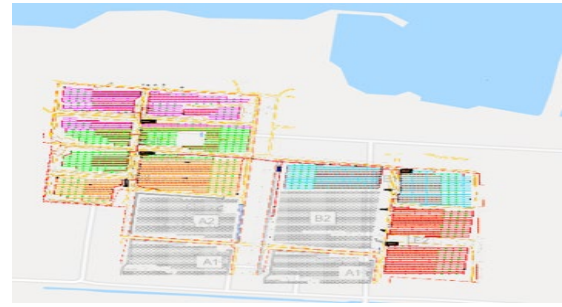

Figure 5. The measurement on the GSs of PV blocks in a park has confirmed the efficiency saturation for each one of them

resistance value measured was on average R_{Gmes} = 0.11 Ω that confirms the diameter D_{MAX} of the maximum area efficient to disperse the fault current of the GMS around the fault point

$$D_{MAX} = 20\ /2*0.11 = 90.9\ m = 4.5|\rho| \qquad (18)$$

lower than half value of the diameter of each GS. Let us note that anyhow the integration of all the park blocks is able to guarantee everywhere the minimum value of the impedance R_{Gmin} seen from the fault point.

C. Third sample case

The third sample case is that of a large GS of an electrical station serving a thermoelectric power plant with a combined CHP. The grounding system has the sizes long a = 240 m and wide b = 80 m constituted by a ground grid electrode with meshes 5 by 5 m in the central area and 10 m by 10 m in the area around (Figure 6).

The soil resistivity was measured as ρ =25.1 Ω/m and the measurement conditions were clear weather.

The relations (16) and (17) applied at this case calculate respectively D equal to 203.71 m and R_{Gp} equal to 0.06 ohm. The current probe was positioned at 330 m from the border of the GS and therefore at more than one and a half times the D of the equivalent circle.

The ground resistance value measured with the voltage probe at 180 m was R_{Gmes} = 0.12 Ω that confirms the diameter D_{MAX} of the maximum efficient area of the GS is lower than the actual diameter of the GS
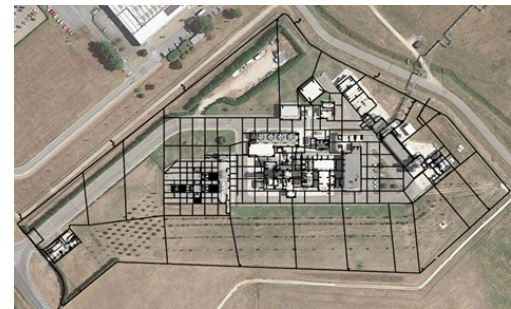

Figure 6. The measurement on a large GS in a soil of low resistivity confirms its efficiency limited to a part of the ground electrode around the fault point

$$D_{MAX} = 20\ /2*0.12 = 104.58\ m = 4.2|\rho| \qquad (19)$$

about half value of the diameter of the actual GS that anyway guarantees for a fault in each internal component to be protected the minimum value of the impedance R_{Gmin}.

V. CONCLUSIONS

The IEC approach provides for a global grounding system, involving users and utilities, as an optimal solution to guarantee the safety of systems in metropolitan and commercial areas, but states that only the utility can validate its existence. The present trend in Europe is to operate the MV distribution with a resonant grounding system that determines fault currents in the order of 50-70 amperes and the adoption of ground fault protection-tripping times greater than 10 s.

Therefore, the GS has to be equivalent to an intrinsic safety grounding system ISGS, because for the tripping time ≥ 10 s it has to satisfy the conventional touch voltage limit HV-U_L=80 V or cautiously the LV-U_L=50 V due to the coexistence of MV-GSs and LV-GSs. In metropolitan and commercial areas, a grounding microgrid systems GMS improving the natural integration among adjacent grounding systems of users, contributes positively to guaranteeing safety. A GMS does not require approval of the utility, because it can be identified by measurements on each GS component. These measurements will confirm for each one of GS under test the membership to the GMS when it is verified a functional efficacy well beyond over its own constitution. The utility can still adhere to the integration and promote a general review of the safety requirements in the condition of global grounding system.

International standards must provide for a new vision of the grounding system in metropolitan and commercial areas of electrical use, recognizing the effective and positive interaction between grounding systems.

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BIOGRAPHIES

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