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Dangerous touch voltages in buildings: The impact of extraneous conductive parts in risk mitigation

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Dangerous Touch Voltages in Buildings: the Impact of Extraneous Conductive Parts in Risk Mitigation

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Abstract—International (IEC) European (CENELEC) and American (NEC) Standards require, in each building, the connection of extraneous conductive parts (i.e. metal water or gas pipes) to the main grounding terminal. There are two good reasons for this: the voltage between extraneous conductive parts and exposed conductive parts is zeroed and extraneous conductive parts can contribute to the leakage of fault current into the ground. There is however a third advantage in the bonding connection: the entire structure (floors and walls of the building), together with the exposed and the extraneous metallic parts, forms a quasi-equipotential system, with the consequent strong reduction of touch voltages. Metallic pipes and reinforcement of reinforced concrete have a particular relevance thanks to their large widespread through buildings. However, in some practical cases, it is not possible to connect all extraneous conductive parts to the protective equipotential bonding because they are not accessible. In the paper, the reduction of touch voltages in buildings, when these extraneous conductive parts are present but not connected to the protective equipotential bonding is quantified. Different building models are created and solved by the finite element method in order to calculate touch voltages in different scenarios. The results show that the mere presence of widespread metallic parts in buildings helps to reduce touch voltages, but not enough to ensure safety against indirect contacts. The electrical installation safety performance is greatly improved in reinforced concrete buildings if at least some easily accessible parts, like water or central heating pipes, are connected to the main

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grounding terminal. Also in brick buildings, they provide a certain reduction of GPR, maximum and mean touch voltages.

Keywords— Equipotential bonding; extraneous conductive part; indirect contacts; protection against electric shock; touch voltage; reinforced concrete

1 ACRONYMS

AQE – Average Quality Element of a mesh

CPE – Control Parameter Error

ECP – Exposed Conductive Part

EXCP – Extraneous Conductive Part

FEM – Finite Element Method

GEC – Grounding Electrode Conductor

GPR – Ground Potential Rise

MGT – Main Grounding Terminal

NEC – National Electric Code

PE – Protective Conductor (IEC) or Equipment Grounding Conductor (NEC)

SLGF - Single Line to Ground Fault

2 INTRODUCTION

An electric shock can be caused by a direct or by an indirect contact with energized parts [1]. In this paper the focus is on indirect contacts inside buildings. An indirect contact is defined in the International Standard IEC 60364-1 [2] [2]as "contact with conductive parts normally not energized, but likely to become live upon faults (e.g., enclosures of equipment)." The effects of electric current on persons depend mainly on the magnitude and duration of the current itself. Based on this, protection methods against indirect contacts are mainly founded on equipotentialization techniques (to reduce the current magnitude) and on the adoption of protective devices such as circuit breakers or fuses (to limit the persistence time) [3].

The automatic disconnection of supply in case of fault is one of these methods and it is based on both the principles described above. In fact, on one hand IEC 60364-4 [4] defines the maximum disconnection time of protective devices and, on the other hand, it

states that the grounding conductor, the main grounding terminal (MGT) and the extraneous conductive parts (EXCPs) shall be connected to the protective equipotential bonding.

According to the definition of the International Electrotechnical Vocabulary IEC 60050-826, EXCPs are "conductive parts not forming part of the electrical installation and liable to introduce an electric potential, generally the electric potential of a local earth" [5]. EXCPs are characterized by a resistance to ground, R_{EXCP}, lower than 1000 Ω [2].

The EXCPs to be connected to the protective equipotential bonding are:

- metallic pipes supplying services into the building;
- structural metalwork if accessible in normal use;
- metallic central heating and air-conditioning systems;
- metallic reinforcement of constructional reinforced concrete, if reasonably practicable.

The North American National Electric Code (NEC) [6] has similar requirements for grounding and bonding. Although the approach is quite different [7], the goals are the same [8]. NEC requests that metal underground water pipes, metal frames of the building, concrete-encased electrodes, and all the "intentional" grounding electrodes (ground ring; rod and pipe electrodes; plate electrodes, etc…) shall be bonded together to form the grounding electrode system [6].

In case of Single Line to Ground Fault (SLGF), the connections required by both IEC 60364-4 [4] and NEC [6] bring two main advantages [9]–[11]:

- all the interconnected metallic parts contribute to the leakage of the fault current, thus reducing the equivalent ground resistance of the earthing system;
- the electric potential differences among all the metallic parts are reduced, producing a nearly equipotential condition [8].

Both these effects can be appreciated in Fig. 1, which refers to a TT system. The resistance to earth of the EXCP, R_{EXCP}, is in parallel with the resistance to earth of the LV User ES, R_{ES}, contributing to the leakage of the fault current. Moreover, the

Exposed Conductive Part (ECP) and the EXCP are interconnected to the MGT through the Protective Conductors (PEs), holding the voltage between metallic parts down.
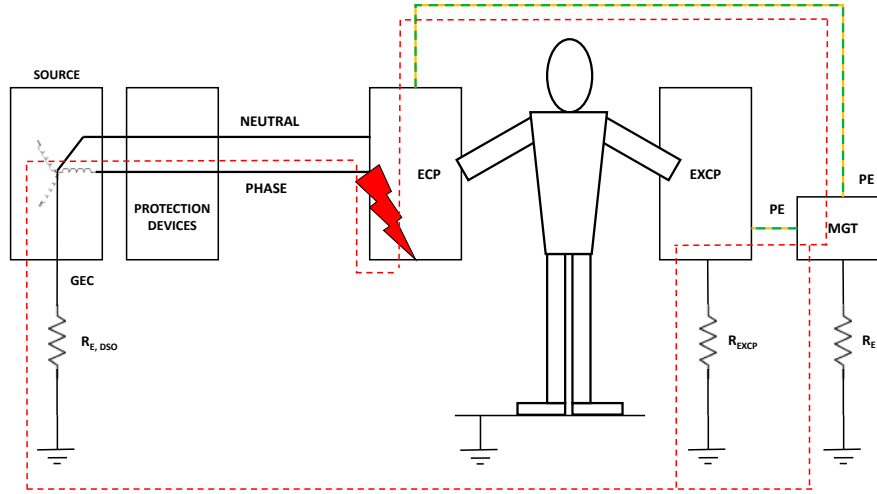

Fig. 1 – Benefit of bonding MGT, ECPs, EXPCs. The resistances $R_{E,DSO}$, R_{EXCP} and R_E are respectively the resistance to earth of the MV/LV substation ES, of the EXCP and of the LV user's ES.

In addition to this, the connections increase the electrical potential of floors and walls too, in a way that depends on the building properties (e.g. the building materials employed or the number of encased metal parts). The more this effect is noticeable, the more a quasi-equipotential condition can be achieved, with a reduction of touch voltages. In this paper, this latter effect is investigated. Even if the benefits of the wired equipotential bonding are well known by the international standard institutions since a long time [4], [12], some aspects have not been clarified yet. In literature, many researchers emphasize the reduction of touch voltages between an ECP and an EXCP due to electrical bonding (hand to hand contact); vice-versa, according to the Author's knowledge, the equipotentialization effect in case of contact with only an ECP (hand to feet contact) has not been discussed yet. In particular, it is not clear if a wired connection among the metallic reinforcement of constructional reinforced concrete, other EXCPs, and the main grounding terminal (MGT) is strictly needed to obtain a consistent reduction of the touch voltage or, instead, just the presence of these metallic parts could be sufficient to improve electrical safety.

A quantitative investigation of the equipotentialization effect introduced by metal parts encased in buildings, to the authors' knowledge, is not available in the scientific literature yet.

In this paper, different scenarios are simulated in order to understand the contribution of non-connected metallic parts to the reduction of touch voltages in buildings. The models refer to a TT system, in which a SLGF has occurred. For each scenario, the floor and walls potential profile is computed, taking into account different situations defined by different building construction typologies (reinforced concrete or masonry), different wired connection configurations, different kinds of foundations and different grounding systems.

For each scenario, a model is implemented and solved by the finite element method (FEM), that allows to simulate systems with complex geometry and electrical discontinuities [13]–[16] .

Different resistivity values of building materials are also used, according to field measurements carried out by the authors in a previous work [17].

3 METHODOLOGY

The building models are built and solved by using the FEM software COMSOL Multiphysics [18]. The verification and validation of the software was carried out in previous works [19], [20].

In the paragraphs below, the implemented building models and the method settings are discussed. Details about the touch voltage computation are also given.

3.1 BUILDING STRUCTURE: GEOMETRY AND MATERIALS

For the models definition, the foundation type, the presence of embedded metal pipes, the grounding system geometry, the choice of the soil and building materials electrical properties and, of course, the connection configuration among metallic parts are the points taken into account. The main geometrical details and material properties about the models implemented are presented in Table I and III respectively.

3.1.1 Foundation type

Several kinds of foundation can be adopted in building design. In this paper, spread footing (Fig. 2-a) and mat-slab (Fig. 2-b) foundations are taken into account for their large diffusion in residential buildings.

The spread footing foundation is a structural unit, which transfers and distributes load to the underlying soil at a pressure consistent with the requirements of the structure and the supporting capacity of the soil. It is generally a rectangular prism of concrete, larger in lateral dimensions than the column or wall it supports [21].

Mat-slab foundation is instead a continuous thick-slab foundation supporting an entire structure. It is typically used if soil conditions are poor [22].
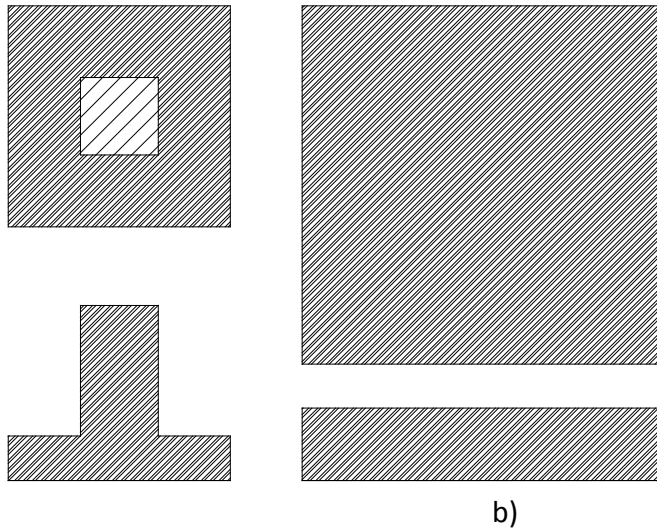

b)

Fig. 2 – Considered types of foundation: a) spread footing foundation; b) mat-slab foundation

3.1.2 Presence of embedded metal parts: Construction Method

Two cases are explored: brick (Fig. 3-a) and reinforced concrete (Fig. 3-b) buildings. Geometrical details are reported in Table I. It is important to highlight that in order to simplify the geometry definition and the mesh creation in the FEM software, typical geometrical dimensions of rods for reinforced concrete are not respected in the model: in real buildings they are more, smaller and closer. The adopted configuration is however a conservative approximation: the less the number of rods, the more difficult achieving a quasi-equipotential area.

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TABLE I
GEOMETRIC CHARACTERIZATION OF THE MODELS

Part	Geometrical dimensions [m]
Building	
Floor surface area	10 x 7
Room height	3
Floor and wall thickness	0.4
Spread footing foundation length	0.25
Reinforced concrete	
Rod radius	0.02
Center to center distance along x-axis	1.7
Center to center distance along y-axis	1.2
EXCPs	
Pipe radius	0.02
x length (external wall y = -3.5 m)	9.7
x length (internal wall y = 0 m)	5.0
x length (external wall y = 3.5 m)	2.5
y length (external wall x = -4.9 m)	6.1
Radiator type 1 area	0.8 x 0.68
Radiator type 2 area	0.4 x 0.68
Earthing System	
Earth rod radius	0.02
Earth rod length	1
Ground ring radius	4

The iron rods, if present, are electrically connected one another in all the scenarios.

3.1.3 *Presence of embedded metal parts: Plumbing*

Metallic radiators and water pipes are considered. In all the evaluated scenarios, pipes are connected the ones with the others and located in the internal and external walls.

The same non-homogeneous layout of the metallic pipes on the floor surface was chosen for all the scenarios (Fig. 3-c), in order to evaluate their effects on the reduction of touch voltages. In the model, EXCPs do not import any extraneous electrical potential.

3.1.4 *Grounding system*

The geometry and the position of the grounding system can influence the potential distribution in the building floor and walls, mainly for two reasons. First, its geometry impacts on its earth resistance value [2] and, consequently, on the Ground Potential Rise (GPR) [2]. Second, the shape of the grounding system and its position with respect to the building can result in different transferred potentials.

For this reason, a per-unit analysis that normalizes the results to the GPR, for all the scenarios, was carried out (as explained in the subsection 3.3) and three grounding system typologies were simulated:

a. a ground ring enclosing the building;

b. a ground rod placed in the center of the structure, reported as an example in Fig. 3-d;

c. a ground rod placed far from the structure. In this case, the electric potential in the proximity of the structure is not directly perturbed by the current field produced by the grounding system.

3.1.5 Soil and building materials electrical properties

The electrical resistivity of soil is a function of the soil constituents (particle size distribution, mineralogy), of the presence of voids (porosity, pore size distribution, connectivity), of the degree of water saturation (water content), of the electrical resistivity of the fluid (solute concentration) and of temperature [23], [24].

In the same way, the electrical resistivity of building materials also depends on the material properties and on the environmental conditions (e.g. concrete, being hygroscopic, attracts moisture [25]). When buried, a concrete block behaves like a semiconducting medium with a resistivity of 30-90 Ωm [25]. Instead, for a dry concrete, resistivity can reach up to 21 GΩm [26].

In a previous paper [17], the authors measured with the fall of potential method the volume resistivity of building materials, such as bricks and samples of concrete. Four different values of dc voltage (i.e. 100 V, 200 V, 300 V and 400 V), were applied to the same test sample for one minute. Details of the experience can be found in [17]. The test results for brick and concrete samples, conditioned in different ways, are reported in Table II.

TABLE II
RESISTIVITY FOR BUILDING MATERIALS [$k\Omega \cdot m$] IN DIFFERENT ENVIRONMENT
CONDITIONS, MEASURED AT DIFFERENT VOLTAGES [V]

VOLTAGE	Bricks			Concrete	
	Dry	Moistened	Wet	Dry	Wet
100	11.4	6.5	0.060	3100.0	0.4
200	7.5	4.4	0.054	1700.0	0.4
300	5.5	3.6	0.050	1200.0	0.4
400	4.3	2.0	0.049	800.0	0.4

In order to quantify how this variability can modify the building potential distribution, two values of electrical resistivity were chosen, both for the building materials and for the soil, as reported in Table III. For all the materials, the value of relative electrical permittivity was set equals to 1, as in first approximation the polarization effects in the domains can be neglected.

TABLE III
MATERIALS PROPERTIES OF THE MODELS

Material	Electrical Conductivity [S/m]
Iron	$1.12 \cdot 10^7$
Building material 1	10^{-2}
Building material 2	10^{-3}
Soil 1	10^{-2}
Soil 2	10^{-3}

3.1.6 Connections configuration among rods of reinforced concrete, water pipes and the MGT

All the possible connection combinations are investigated; in this way, the prospective touch voltage reduction due to the interconnection between the MGT and the encased metallic parts can be evaluated. The examined scenarios are summarized in Table IV. As an example, Fig. 3 shows for case 1 the elements considered in the model. The complete model is shown in Fig. 4: the reinforcement is drawn with blue dashed lines, the water pipes and radiators with green solid lines, the grounding system with a red dash-dot line.

3.2 FEM METHOD SETTINGS

As previously said, the building models are built and solved using the FEM method. According to the evolution of the field quantities (time periodic, 50 – 60 Hz) and to the

small geometrical dimensions of the models implemented, a stationary electric current study has been carried out.

The FEM software solves a current conservation problem for the scalar electric potential V [13]–[16], [18].

In order to present the simulation setup, unbounded soil modelling, boundary conditions and mesh properties are discussed in the paragraphs below. A control parameter to verify the results is also defined.
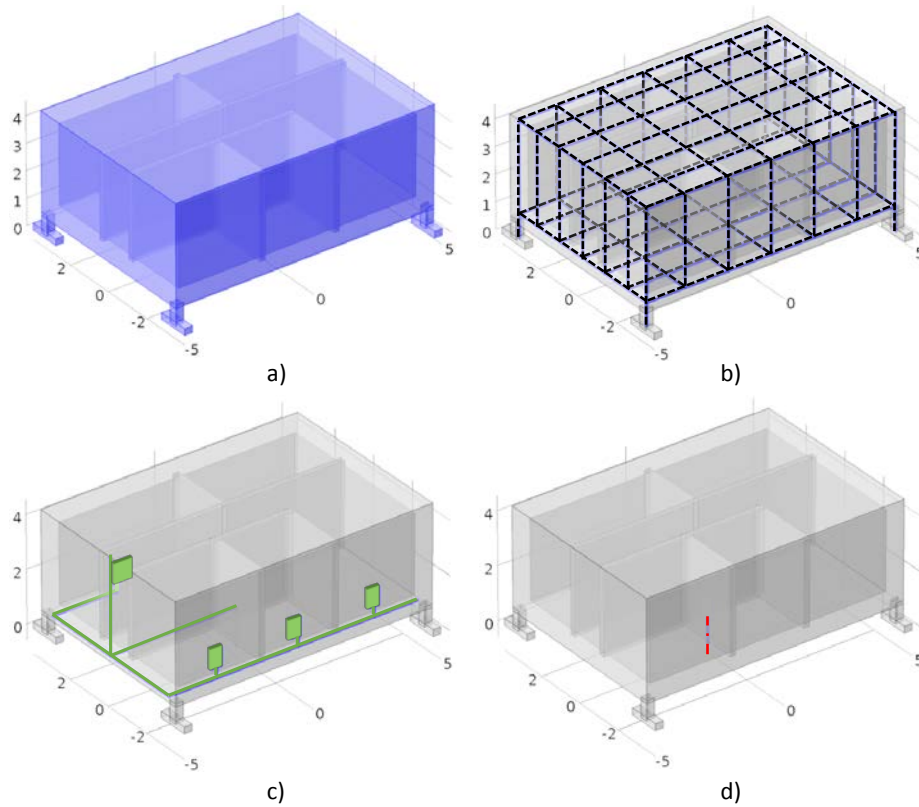

Fig. 3 – Case 1 – Model elements: a) walls; b) reinforcement of reinforced concrete; c) water pipes; d) grounding system
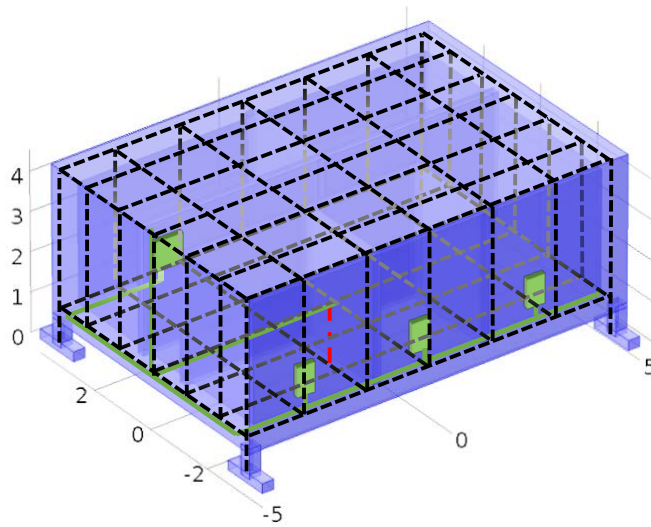
Fig. 4 - CASE 1 - Complete model

TABLE IV
EXAMINED SCENARIOS

Factor	Case N°									
	1	2	3	4	5	6	7	8	9	10
Foundation										
Spread footing	✓	✓	✓	✓	✓	✓				
Mat-slab							✓	✓	✓	✓
Method of construction										
Reinforced concrete	✓	✓	✓	✓	✓	✓	✓			
Brick build								✓	✓	✓
Grounding system										
Ground ring						✓				
Earth rode	✓	✓	✓	✓			✓	✓	✓	✓
Far earth rode					✓					
Soil resistivity										
Soil 1	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Soil 2										✓
Building resistivity										
Material 1	✓	✓	✓		✓	✓	✓	✓	✓	✓
Material 2				✓						
Wired connection between reinforcement and MGT										
Present	✓							-	-	-
Absent		✓	✓	✓	✓	✓	✓	-	-	-
Wired connection between pipes and MGT										
Present	✓	✓		✓	✓	✓	✓	✓		✓
Absent			✓						✓	

3.2.1 *The soil: an unbounded domain*

The analysis involving grounding systems shows the need for including open boundaries of the ground. In fact, all the electric potentials relate to the reference earth, i.e. a part of the Earth whose electric potential is conventionally taken as zero, being outside the zone of influence of the earthing arrangement [27].

In order to model infinity correctly without increasing the size of the problem, the method based on spatial transformation was adopted [28].

This implementation maps the model coordinates from the local, finite-sized domain to a stretched domain. The inner boundary of this stretched domain coincides with the local domain, but at the exterior boundary the coordinates are scaled toward infinity [28]–[30].

3.2.2 *Boundary conditions*

Ground was modelled as an unbounded domain, thanks to the COMSOL infinite element based on [29]. The external boundaries potential are set equal to 0 V (reference earth) [27]. It was also imposed that no electric current could flow through the remaining external boundaries of the simulated domain.

In order to generalize the results, taking advantage of the fact that the modelled system is linear, the earthing systems inject into the ground a current of 1A.

3.2.3 *Mesh*

Tetrahedral elements are used in meshing the model. In COMSOL Multiphysics, the quality of an element is a value between 0.0 and 1.0, where 0.0 represents a degenerated element and 1.0 represents a completely symmetric element. For each model implemented, the average element quality (AEQ) is evaluated and reported in Table V.

3.2.4 *Control Parameter*

In order to assess the goodness of simulation, current is used as control parameter: the currents flowing into the ground should be equal to the sum of currents flowing out of the boundary. For each model implemented, the control parameter error (CPE) is evaluated by (4) and reported in Table V.

$$CPE = \frac{I_{in} - \iiint_S \|J_{out}(x,y,z)\| \, dxdydz}{I_{in}} \cdot 100 \qquad (1)$$

Where I_{in} is the current injected by the grounding system and $\|J_{out}(x,y,z)\|$ is the normal current density (A/m^2) in the point with x, y, z coordinates. *S* is the external ground surface, not considering the infinite element. The higher the CPE, the more unreliable the computed results. As the maximum CPE is just 0.5%, the results of the simulations can be considered reliable.

TABLE V
CONTROL PARAMETER(CPE) [%] AND AVERAGE ELEMENT QUALITY (AEQ)

	Case N°									
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
AEQ	0.64	0.66	0,66	0.66	0.66	0.76	0.64	0.70	0.71	0.71
CPE	0.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

3.3 TOUCH VOLTAGE AS AN ELEMENT OF ASSESSMENT

The international standard IEC 60479-1 [31] defines the conventional time/current zones of effects of current on persons. As far as the ventricular fibrillation is concerned, it considers as a reference the current path from left hand to both feet. For this reason, in order to evaluate the reduction of touch voltage due to the presence of reinforcement of reinforced concrete and metal pipes, for all the scenarios described above, only this current path is contemplated; the difference between the potential of ECPs and the potential of the floor is therefore to be computed.

In this analysis, the potential of ECPs is considered equal to the GPR, because of the interconnection through PE conductors.

The considered situation is a SLGF in an electric appliance, which energizes an ECP, as showed in Fig. 5; the connections 'A' and 'B' highlighted Fig. 5 can be present or not, depending on the simulated scenario.
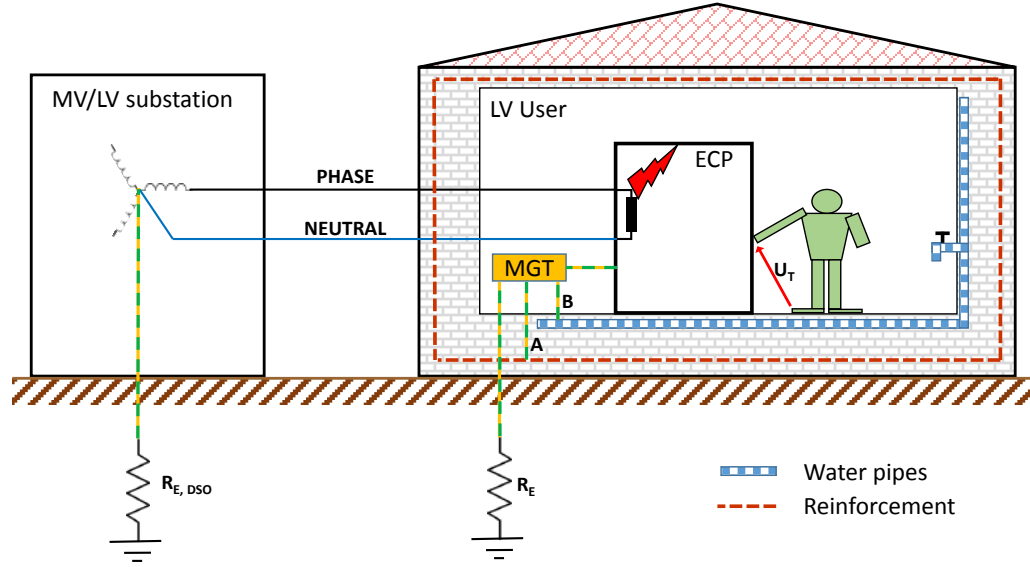
Fig. 5 - Considered situation - SLGF in an electrical appliance

The analyzed floor surface is highlighted in Fig. 6, to facilitate reading results; it refers to geometry model of case 1.

As the electrical potential profile on the floor surface is not constant, the touch voltage $U_T(x, y)$ depends on the coordinates x and y where the person is standing: with reference to the GPR it can be expressed as in (5):

$$U_T(x, y) = \frac{GPR - U_F(x,y)}{GPR} \cdot 100 \qquad (2)$$

where $U_F(x, y)$ is the potential on the floor in the point with x, y coordinates.
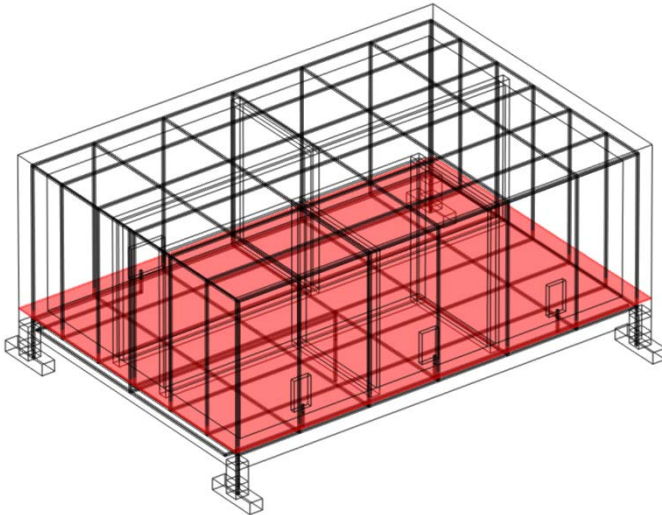

Fig. 6 - CASE 1 – Floor surface

4   RESULTS

Table VI shows the GPR in volt, as well as the maximum and mean values of U_T as

percentage of GPR, when the grounding system injects a current of 1 A.

In the following paragraphs, the ten cases are analyzed in detail.

TABLE VI
GROUND POTENTIAL RISE [V] AND MAXIMUM AND MEAN VALUES OF U_T
REFERENCED TO GPR [%] FOR AN INJECTION CURRENT OF 1 A

Case N°										
	1	2	3	4	5	6	7	8	9	10
GPR [V]	22.5	23.3	61.6	47.9	22.8	4.9	6.2	7.5	52.9	54.2
$U_{T\,Max}$[%]	0.4	5.5	95.6	10.4	5.7	2.6	26.2	67.8	94.4	32.0
$U_{T\,Min}$ [%]	0.0	4.8	95.6	8.9	4.9	2.1	20.2	34.3	90.4	11.7

4.1   Reinforced concrete buildings with different connections to MGT, grounding system, building resistivity and foundation type

In this section, reinforced concrete buildings are considered.

Case 1 models a typical building, with reinforcement and pipes connected to the MGT as recommended by standards [4], [6]. It has spread footing foundations and an earth rod as grounding system. Soil and building materials have a resistivity of 100 Ωm.

Case 2 differs from the previous one, as there is no wired connection between the reinforcement of reinforced concrete and the MGT.

Considering this scenario as the base case, models to evaluate the impact of each influence parameter have been obtained, varying the building properties one by one.

4.1.1   Case 1 – Wired connection among MGT, pipes and reinforcement

The reinforcement of reinforced concrete and the water pipes are connected to the MGT. This is the configuration recommended by IEC 60364 [4] and NEC [6]. The difference between the maximum and mean values is 0.4% of the GPR: metal parts form a quasi-equipotential surface. The grounding system and the floor surface have about the same potential.

IEC 60364 [4] considers 50 V as the maximum admissible touch voltage for general environmental conditions. As the maximum U_T is less than 0.5% of the GPR and the GPR cannot exceed 1kV for low voltage systems, no electric shock danger is present.

4.1.2   Case 2 – Reinforcement disconnected

This scenario differs from the previous case as there is no wired connection between the reinforcement of reinforced concrete and the MGT. Although not connected to the ground, metal parts constitute a quasi-equipotential surface. The difference between the maximum and mean touch voltage value is 0.7% of the GPR. For general environment conditions, when the voltage on ECPs is lower than 1 kV, no dangerous touch voltages are present as the maximum touch voltage is just 5.5% of the GPR.

This result is relevant for all existing reinforced concrete buildings where the reinforcement is not joined to the MGT.

4.1.3   Case 3 - Reinforcement and pipes disconnected

In this case neither the metal pipes nor the reinforcement are connected to the ground. The U_T profile is approximatively flat even if, in this case, the mean touch voltage is about 96% of the GPR. These results prove that, in order to decrease touch voltages, it is important to connect at least some EXCPs to the MGT. It is also essential that the connected EXCPs are quite widespread throughout the building.

4.1.4   Case 4 - Building resistivity

This model is geometrically the same as case 2. Only the resistivity of the building material is ten times higher (10^3 Ωm), in order to explore the range of values reported in Table II.

Even if the touch voltage distribution is approximately flat as in case 2, the magnitude increases by about 50% as shown by the maximum and mean touch voltage values in Table VI. The GPR increases by about 50% too.

The increase in GPR can be explained because, in this case, the grounding system is connected to the water pipes, which have in their surroundings a material with a higher resistivity [32].

Extending the results of this simulation to all the others scenarios, it is possible to infer that increasing building material resistivity, the GPR and the touch voltage distribution increase as well.

4.1.5 Case 5 - Far earth rod

For the scenario considered, the grounding system is geometrically the same as in case 2. The difference lies in the relative position between the grounding system and the building. This time, the electric potential in the proximity of the structure is not directly perturbed by the current field produced by the grounding system. Both the touch voltage profile (approximately flat) and the results reported in Table VI show that no relevant differences are present between case 2 and 5.

4.1.6 Case 6 - Ground ring

The current field in the ground depends on the geometry of the grounding system adopted. Case 6 is similar to case 2, with the exception of the grounding system. A ground ring runs near the metal rods inside the spread footing foundation, surrounding the building. The touch voltage profile is approximately flat. By comparing the results obtained for case 2 and 6, no significant differences can be observed.

4.1.7 Case 7 – Foundation

It is possible to evaluate the effect of the foundation type by comparing the results for cases 2 (spread footing) and 7 (mat-slab). Also in this case, a wired connection is only present between the pipes and the MGT while the reinforcement is floating.

It is worth noting the significant GPR reduction. This is due to the reinforced concrete that also drives the fault current directly into the ground. The touch voltage distributions of case 2 and 7 have approximately the same trend since, as in case 2, the reinforcement forms a quasi-equipotential surface.

4.2 Brick buildings with different connection to MGT and soil resistivities

In this section, brick buildings with a mat-slab foundation are considered. Note that the distribution of water pipes is non-homogeneous, in order to evaluate better its effect on the touch voltage reduction.

4.2.1 Case 8 – Wired connection between MGT and pipes

The foundation type and the presence of metal parts joined to the grounding system reduce the GPR and touch voltages. As shown in Fig. 7, where the water pipes lay more numerous, touch voltages are about 30% of the GPR. The exact position of the pipes can be easily located: there, the touch voltage is approximately zero. Where no

embedded metallic parts are present, touch voltage grows fast. In the top-right corner, just a few meters away, it is about 70% of the GPR.

4.2.2 Case 9 – No wired connection between MGT and pipes

This case is very similar to the previous one; the difference lies in the lack of a wired connection between the pipes and the MGT. By comparing the results for cases 8 and 9 (Fig. 7 and Fig. 8), it is possible to evaluate the importance of the wired connection among the metallic pipes and the MGT, especially in brick buildings. Without the wired connection, in fact, the GPR, the maximum and the mean values of touch voltages are increased by 605%, 882% and 1768%, respectively. The embedded metal parts, if not connected, do not produce any significant effect. Vice-versa, if connected and sufficiently widespread, they can significantly reduce both GPR and touch voltages.
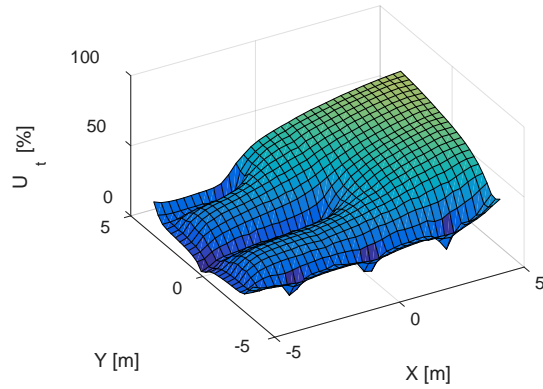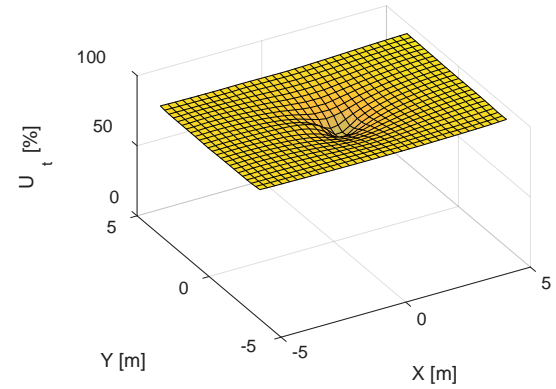

Fig. 7 - $U_t(x, y) - Case\ 8$ *Fig. 8 - $U_t(x, y) - Case\ 9$*

4.2.3 Case 10 – Soil resistivity

The wider the contact surface between the structure and the ground, the more evident the effects of soil resistivity in altering the electrical potential distribution inside the building. For this reason, in order to investigate the influence of soil properties, the mat-slab foundation is chosen. In this scenario, a sandy soil is simulated. This is the only difference with respect to case 8. By comparing the results for cases 8 and 10, it can be seen that in the latter the GPR is increased due to higher soil resistivity, but the percent touch voltage is decreased. In fact, a higher soil resistivity reduces the steepness of the potential profile (Fig. 9).
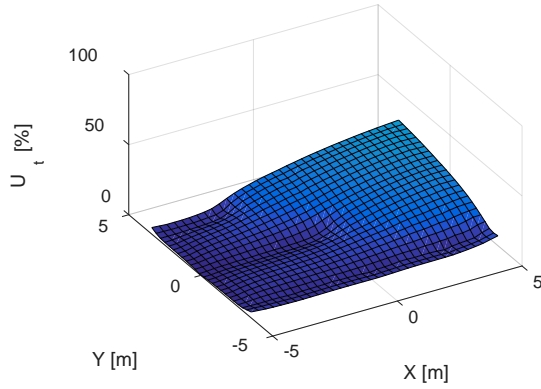
Fig. 9 - $U_t(x, y)$ − Case 10

5 CONCLUSION

Different scenarios are simulated in order to evaluate the contribution of embedded metallic parts, not connected to the MGT, to the reduction of touch voltages in buildings. For each of them, with reference to the TT distribution system, a model is implemented and solved by the finite element method.

According to the results of the simulations, reinforcement of constructional reinforced concrete and others EXCPs reduce touch voltages in all the evaluated scenarios. Even if the wired connections among metallic reinforcement of constructional reinforced concrete, other EXCPs and the MGT is recommended, the mere presence of these metallic parts, without intentional connections, contributes to the reduction of touch voltages.

The electrical installation safety performance is greatly improved if a building is made of reinforced concrete and at least some easily accessible parts like water or central heating pipes are joined with the MGT. For old buildings, where the reinforcement of concrete was not connected to the equipotential bonding, it may therefore be sufficient to connect metallic pipes of water, sewage and heating systems. This operation is easy and cheap and according to the models implemented for this scenario, touch voltage is reduced up to 5% of the GPR.

Also in brick buildings, if EXCPs are widespread and joined to the MGT, a significant reduction of GPR, maximum and mean touch voltages can be achieved: for the particular scenario considered in this paper the interconnection provides a reduction of about 86%, 90% and 95% of the three performance parameters respectively.

The higher soil resistivity and narrower contact surface between the structure and the ground, the more evident this reduction.

For what concerns the topics discussed in this paper, geometry of the grounding system is only relevant for the value of the GPR. Increasing the distance between grounding system and building does not significantly modify the touch voltages distribution.

IEC 60364 [4] considers supplementary protective equipotential bonding as a valid method to ensure the protection against indirect contacts. The results obtained and presented in this paper confirm the goodness of this practice.

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