Electrical Safety Analysis in the Presence of Resonant Grounding Neutral

Massimo Mitolo
Senior Member, IEEE
Irvine Valley College
Electrical Department
5500 Irvine center Drive
Irvine, CA 92618, USA
mitolo@ieee.org

Rossano Musca
Università di Palermo
Engineering Department
viale delle Scienze, Edificio
8, 90128 Palermo, Italy
rossano.musca@unipa.it

Michele Tartaglia
Senior Member, IEEE
Politecnico di Torino
Department of Energy
Corso Rodolfo
Montevecchio 71, 10129
Torino, Italy
michele.tartaglia@polito.it

Gaetano Zizzo
Senior Member, IEEE
Università di Palermo
Engineering Department
viale delle Scienze, Edificio
8, 90128 Palermo, Italy
gaetano.zizzo@ieee.org

***Abstract*— The resonant grounding is one of the possible methods of system neutral grounding for the medium voltage distribution. IEEE standards do define this grounding configuration, but important advantages and drawbacks of the resonant grounding might not be fully known, due to its rather uncommon application in North America. On the other hand, resonant grounding in Europe is imposed by the increased requirements for power quality, especially for medium-voltage industrial users, imposed to electric utilities by Regulatory Authorities, with the purpose to protect the interests of users and consumers.**

Level of the continuity of the service, magnitude and phase of ground-fault currents, magnitude of touch voltages, all depend on how the neutral is connected to ground. In this paper, the authors will discuss electrical safety features of the resonant ground, and analyze issues when a substation, originally operated with different methods of system neutral grounding, is reconfigured with a resonant ground. In particular, a conservative approach for preserving safety during HV-MV substations' reconfiguration is herein proposed; the cases of the substation reconfiguration from resonant grounding to isolated-from-ground and vice versa shall be analyzed. Finally, the analysis of the impact of the use of Petersen Coil on the Global Grounding Systems will be provided.

***Index Terms*— Ground fault; Petersen Coil; Resonant Ground; Network reconfiguration.**

I. INTRODUCTION

Resonant grounding is one of the possible methods of system neutral grounding [1] for high- to medium-voltage stations. Resonant grounding is primarily adopted in European Countries (Fig.1) [2], but also in most of the medium voltage network in China.

In the event of ground-faults, the type of system neutral grounding dictates how the main electrical quantities vary:

- magnitude and phase of ground-fault currents, which in turn determine the choice of the protective relays;
- magnitude of over-voltages, both transient and at power grid frequency, which in turn determines ratings and coordination of the insulation of electrical equipment.

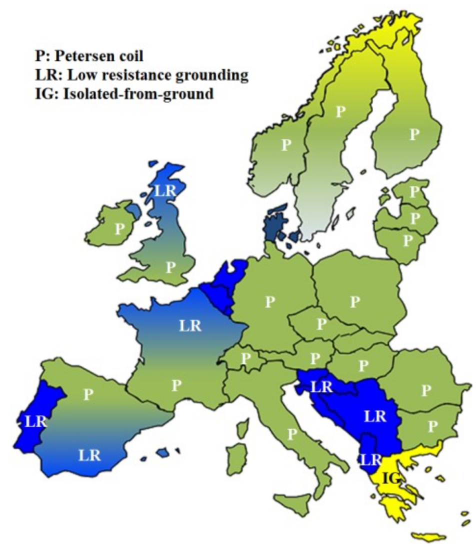

Fig. 1. System neutral resonant grounding in Europe. (green: resonant grounding; blue: low impedance/solid grounding) [2].

The choice of the method of system neutral grounding for high- and medium voltage stations may be based upon the following criteria:

- local regulations (if any);
- continuity of supply required for the power network;
- limitation of damage to equipment caused by ground-faults;
- selective elimination of faulty sections of the power network to guarantee continuity of supply to medium-voltage (MV) users;
- touch and step voltages;

The resonant grounding is chosen to improve the continuity of the electric service by limiting the magnitudes of ground-fault current, and therefore allowing transient faults to be cleared without feeder tripping. The resonant ground, therefore, decreases the probability of power outages for customers, as well as damages to the power network.

The resonant grounding system includes a reactor (also referred to as Petersen coil, after its inventor) connected between the Medium Voltage transformer neutral point and the ground (Fig. 2).

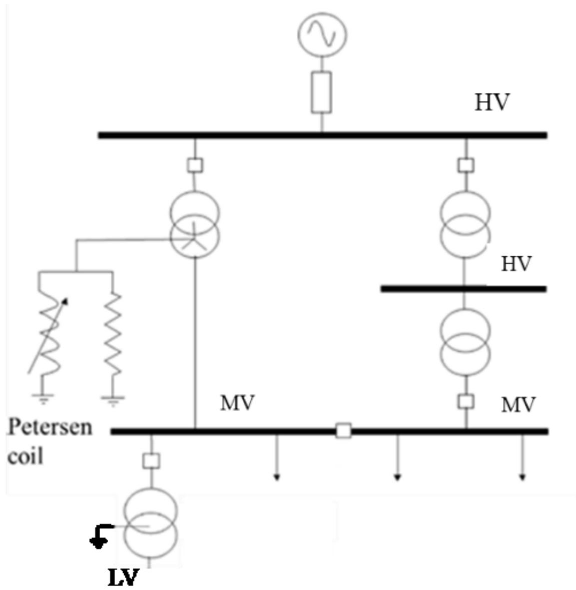

Fig. 2. Typical configuration for resonant grounding HV-MV stations.

In the case of a ground-fault at the MV distribution network, or at the user MV-LV substation, the ground-fault current is composed of three components:

1. the active current $\underline{I}_R$, which is caused by the inevitable losses in the distribution network and equipment.
2. The leading capacitive charging current $\underline{I}_C$ of the resonant grounded system.
3. The lagging compensation inductive current $\underline{I}_L$ from the Petersen coil.

The inductance of the reactor is so chosen to resonate with the distributed capacitance of the power network; if the inductive reactance of the coil is equal to the capacitive reactance of the power network (i.e. resonant condition), the lagging and the leading currents would cancel each other, and the ground-fault current is reduced to the resistive current.

Transient arc ground faults are the most common faults affecting overhead power lines, for example due to atmospheric agents (e.g. rain, wind, snow), moisture on the insulators, or brief contacts with tree branches.

References [3, 4] indicates as 60 A (for 20 kV power grids) the level of current flowing through a transient arc below which most arcs self-extinguish. Higher currents cause air ionization, which supports the arc even if the triggering factor has been eliminated. The ground-fault current value can change country by country according to local regulations, but it is always chosen to be limited to less than 60 A. For example, in Italy, the mandatory standard dealing with the connection of end-users to the MV networks imposes 50 A for 20 kV-distribution grids and 40 A for 15 kV-grids [5].

The coexistence of different methods of system neutral grounding for the medium voltage distributions may be possible in those European nations where a reconfiguration of stations to resonant grounding neutral is in progress [6]. This reconfiguration is dictated by the increased requirements for power quality, especially for medium-voltage industrial users, imposed to electric utilities by European Regulatory Authorities, with the purpose to protect the interests of users and consumers [7].

Reconfigurations are not however devoid of safety issues.

A conservative approach for preserving safety during HV-MV substations' reconfiguration is herein proposed; the cases of the substation reconfiguration from resonant grounding to isolated-from-ground, and vice versa, shall be herein analyzed. In addition, a novel analysis of the impact of the adoption of the Petersen Coil on Global Grounding Systems is provided.

The paper introduces the principles of operation of the Petersen coil in Section II. In Section III, safety conditions in the presence of the resonant grounding are discussed. In Section IV, a conservative approach for preserving safety during HV-MV substations' reconfigurations is proposed. Section V reports some considerations on the thermal sizing of the grounding conductors in the presence of the Petersen coil. Section VI discusses the impact of the resonant grounding on a Global Grounding System and, finally, Section VII contains the conclusions of the paper.

II. Principles of Operation

The principle of operation of the Petersen coil is apparent if we consider the sequence network connections for a single-phase-to-ground fault (Fig. 3) [8].

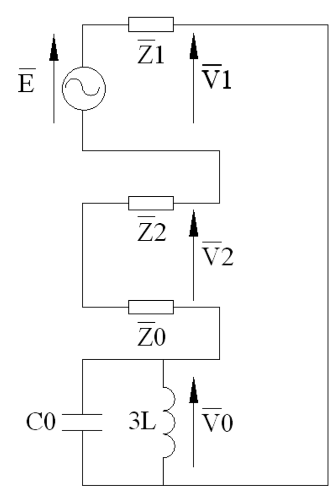

Fig.3. The sequence network for a single-phase-to-ground fault.

For analysis of coil tuning it is common ignore the effect of the positive and negative sequence networks (Z1=Z2=0).

The equivalent circuit is shown in Fig. 4.

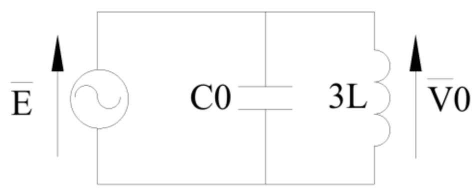

Fig. 4. Equivalent circuit for the sequence network for a single-phase-to-ground fault.

Resonant conditions are achieved for a value of L given in equation 1.

$$3\omega L = \frac{1}{\omega C_0} \quad (1)$$

In dynamic systems, ideal resonant conditions may not always be achievable, as the network zero-sequence capacitance C_0 may vary due to switching on or off lines in the distribution power network. Typically, the switching on/off of long cable runs may cause the need of re-tuning the Petersen coil. There may be cases when the Petersen coil over-compensates or under-compensates the network reactive capacitance.

To guarantee resonant conditions, a control system may automatically adjust the reactance of a moving-core (i.e., plunger) reactor so that to continuously match the network capacitance-to-ground [9]. The adjustment of the coil is performed in healthy conditions of the network, before the occurrence of faults. In practice, the resonant grounding of the neutral point is carried out with an impedance rather than with just a reactance (Fig. 5).

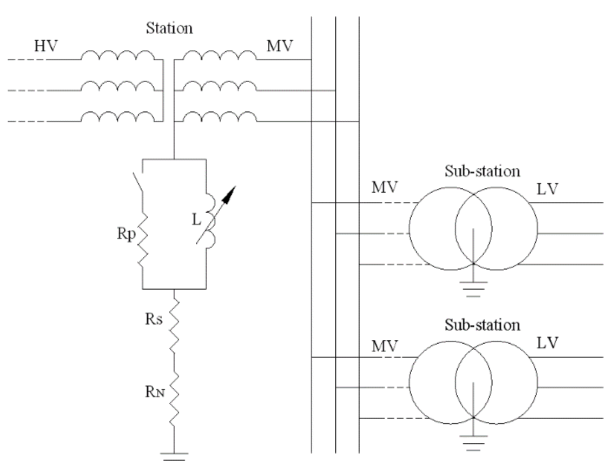

Fig. 5. Complete arrangement for the resonant grounding.

L represents the Petersen coil (patented around 1920), equipped with a moving-core reactor core with an adjustable air gap. The standard method for an automatic tuning consists of incremental changes to the value of the inductance and measurements of the neutral voltage; from a theoretical curve the resonance point can be estimated [10]. More sophisticated tuning techniques may adopt the *injection into the neutral point* method [11] to calculate the proper resonant coil value.

The adjustment of the Petersen coil inductance may also be manually performed, in de-energized conditions, based on the power network configuration at a given time. In this case, the coil is equipped with taps, rather than with an adjustable core.

R_p is a resistor (e.g. 600 Ω) that is connected in parallel to the Petersen coil via a switching on/off controller. Its function is to facilitate the operation of watt-metric directional ground-fault protection relays [12] of HV-MV stations, by increasing the resistive ground-fault current to a level which the outgoing MV feeder protection relays can detect.

This residual current (i.e. power factor close to unity) is obviously not compensated by the coil, and allows the de-energization of the feeder in a certain time if the fault is not momentary. The residual current further facilitates the extinguishing of any arc as both driving voltage and current have almost coincident zero-crossings. Thus, protective relays can ultimately disconnect and isolate the faulty MV distribution line, and prevent the HV-MV station and other MV users from being affected by a possible outage.

R_s represents a resistor in series to the station ground-grid (R_N), whose purpose is to limit the time constant of the DC component of the ground-fault current.

Even though a complete compensation of the ringing current may not be achieved (i.e. 100% tuning), low values of ground-fault currents may still allow the operation of the system with a faulty phase, thereby preserving the continuity of the service.

III. ELECTRICAL SAFETY ANALYSIS

In general, regardless of the method of system neutral grounding of stations, the performance of ground grids of low-voltage (LV) substations (Fig. 2) is crucial for the safety of personnel. When a ground-fault occurs on the primary side of LV substations, a ground-fault current will flow through the ground grid and the soil toward the supply station, and touch and step potentials appear in the premises.

The resistance-to-ground R_G of the substations' ground grid must be as such to limit touch and step potentials within permissible values. The effectiveness of the ground grid depends on the magnitude and duration of ground-fault currents: low-magnitude touch voltages, but associated to longer clearing times may be equally hazardous [13].

In technical standards, harmful body currents as a function of fault duration are generally translated into permissible prospective touch voltages U_{vT}, so that to allow a comparison with calculated touch potentials. The prospective touch voltage is the potential difference between simultaneously accessible conductive parts when those conductive parts are not being touched [14]. References [15] and [16] provide such curves (Figures 6 and 7).

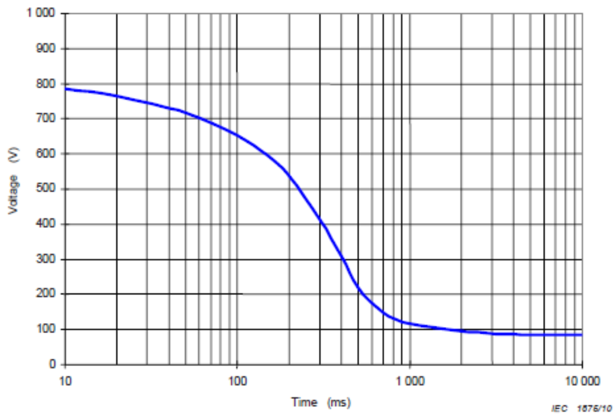

Fig. 6. IEC (International Electrotechnical Committee) Permissible touch voltage U_{Tp} as function of the fault duration (excerpted from [15]).

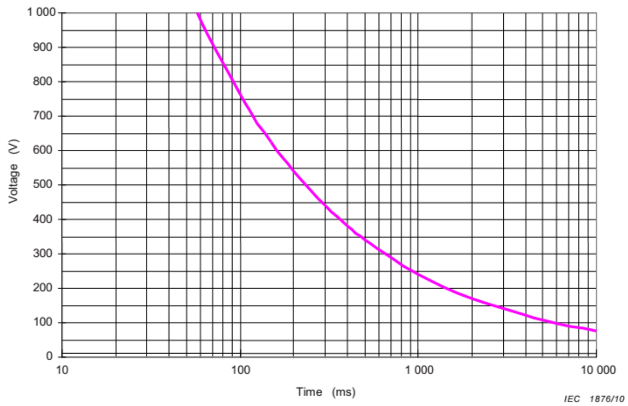

Fig. 7. IEEE 80 Permissible touch voltage U_{Tp} as function of the fault duration (excerpted from [16]).

Reference [14] also indicates that, as a general rule, if the design of the ground-grid satisfies the touch voltage requirements, also satisfies the step voltage requirements. Permissible step voltage limits are in fact much higher than touch voltage limits, thanks to a different current pathway through the body that does not involve the heart [17]-[18]. Consequently, the step voltage magnitude may no longer be employed as a criterion to size grounding grids.

In the case of the resonant ground, the magnitudes of ground-fault current and prospective touch voltage may be low; however, the fault clearing time is positively increased to allow its self-extinction.

Utilities that have reconfigured their substations to resonant grounding provide designers with conventional values for the residual ground-fault current earlier discussed, and tripping times, based on the sensitivity of their existing protective devices, for example, 50 A, and 10 s [5].

As a consequence, utilities design substation ground-grids, so that their resistance-to-ground R_G satisfies (2).

$$\frac{U_{LN}}{R_G} = 50A \qquad (2)$$

where U_{LN} is the system line-to-neutral rms voltage in volts.

Per the curves of Figs. 6 and 7, the maximum permissible touch voltage in correspondence with the time of 10 s is 75 V. This means that to assure safety, the ground potential rise (GPR) must satisfy (3).

$$GPR= 50 \cdot R_G \leq 75\ V \qquad (3)$$

which corresponds to a maximum value for the MV-LV substation ground grid resistance R_G of 1.5 Ω.

The above equation is a conservative statement, as assumes that actual prospective touch voltages can be as high as the GPR, which is not necessarily the case. Thus, Equation (3) provides a sufficient but not a necessary condition for safety.

IV. GROUNDING RECONFIGURATION OF STATIONS

As anticipated earlier, to improve the continuity of the electrical service to MV customers, the reconfiguration of HV-MV stations from isolated-from-ground neutral point (i.e. ungrounded) to resonant grounded neutral point is carried out in many countries.

The grounding reconfiguration is safe if (4) is satisfied.

$$I_{GU} \geq \frac{U_{TP}}{1.5\Omega} \qquad (4)$$

Where I_{GU} and U_{TP} are respectively the ground-fault current, and the maximum permissible touch voltage occurring in an ungrounded neutral HV-MV substation; 1.5 Ω is the maximum value for the ground-grid resistance of the resonant grounded HV-MV substation.

The value of I_{GU} varies with the fault duration t_F according to the curves of Figs. 5 and 6, and can be estimated with a third order polynomial trendline (5).

$$10^{-3} I_{GU} = -t_F^3 + 2.82 \cdot t_F^2 - 1761.1 \cdot t_F + 0.99 \qquad (5)$$

If I_{GU} estimated with (5) for any given fault duration t_F relative to the isolated-from-ground neutral is in compliance with (4), touch voltages occurring at the resonant grounded HV-MV substation will be within safe limits.

As earlier mentioned, (4) is a conservative condition, thus if (4) is not verified, not necessarily unsafe conditions may exist. In this case, the measurement of prospective touch voltages within the substation with a high-impedance voltmeter must be performed, and condition (6) must be satisfied:

$$\frac{U_{vT}^m}{I_T} \cdot 50A \leq 75\ V \qquad (6)$$

where U_{vT}^m is the measured value of the touch voltage, and I_T is the test current employed by the test equipment.

If all values of U_{vT}^{m} satisfy (6), no modifications to the original grounding grid are required. If at least one value of U_{vT} does not satisfy (5), actions shall be taken to improve the ground grid in the new resonant ground configuration [6].

However, there might be cases when MV-LV substations normally operated with the resonant grounding system may be temporarily operated with an isolated-from-ground neutral [6]. This may be due to the necessary maintenance of the Petersen's coil. In some other cases, resonant grounded and existing ungrounded substations may coexist.

In the above situations, the ground-resistance of substations operating with an isolated-from-ground neutral must be less than a permissible value R_{Gp}. R_{Gp} is the value of ground-resistance that must never be exceeded at any point of the ungrounded MV system so that touch voltages are kept within safe magnitudes, calculated according to [15] or [16].

The permissible ground resistance is calculated as the ratio of the permissible touch voltage U_{Tp} to the single-phase-to-ground fault current I_F at the fault location:

$$R_{Gp}=U_{Tp}/I_F \qquad (7)$$

We conservatively neglect the reduction factor of the fault current due to the interconnection of ground-grids to the MV cables' metal sheaths [15].

R_{Gp} has been calculated for ungrounded systems for fault currents ranging between 100 A and 2,000 A, for fault clearance time ranging between 100 ms and 1 s, and by referring to Fig. 6 (other values are found in Fig. 7). The results of the calculations are graphically summarized in Fig. 8.

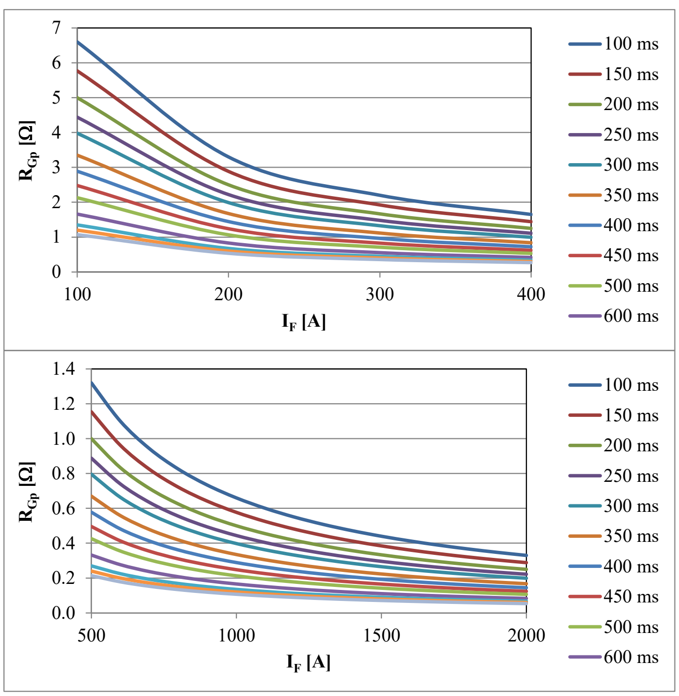

Fig. 8. Permissible ground-resistance.

Considering a given substation isolated from ground, knowing the value of the fault current and the fault clearance time, the permissible ground impedance can be found in Fig. 8. The substation is safe if its ground resistance verifies the condition:

$$R_G \leq R_{Gp} \qquad (8)$$

V. Thermal Sizing of the Grounding Electrode Conductor, and of the Grounding Electrode

The grounding electrode conductor (GEC) is a conductor used to connect the system grounded conductor or the equipment to a grounding electrode or to a point on the grounding electrode system [8]. Alternatively, the GEC is defined as the conductor which provides a conductive path, or part of the conductive path, between a given point in a system or in an installation or in equipment and an earth electrode [8].

According to [8], the minimum size of the GEC of the Petersen coil must be 16 mm² (copper) to guarantee mechanical strength and stability against corrosion. Reference [8] specifies a minimum size of 6 AWG (13.3 mm^2) (copper or aluminum) for the GEC, and if exposed to physical damage, its inclusion in a rigid metal conduit.

The size of the grounding electrode must be conservatively sized according to the magnitude of the double ground-fault current I''_{kEE} (Fig.7), even though I''_{kEE} will not circulate through it [13].

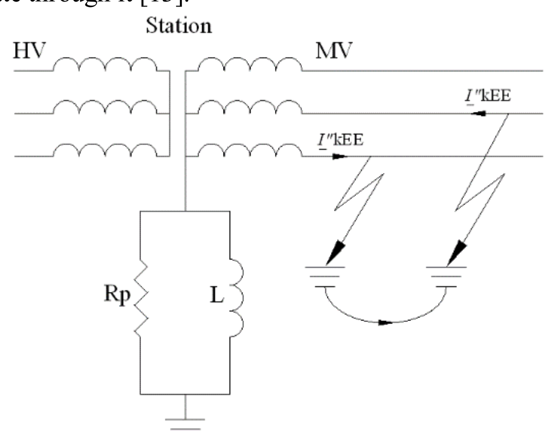

Fig. 9. Double ground-fault.

On the other hand, the GEC to the Petersen coil, must be sized according to the rating of the coil (e.g. 50 A) [14].

Thus, to size the GEC one must determine I''_{kEE} and the related fault clearing time t_F as per the following equation:

$$I_{kEE}^{''2} \cdot t_F \leq K^2 \cdot S_{GEC}^2 \qquad (9)$$

where S_{GEC} is the GEC section and K is the thermal coefficient of the armor given by [15].

VI. IMPACT OF THE PETERSEN COIL ON GLOBAL GROUNDING SYSTEMS

As per the definition in [19], a Global Grounding System (GGS) is an extended grounding system created by the interconnection of several ground-grids and extraneous-conductive-parts (e.g., buried water pipes) in a given geographic area, which ensures that no dangerous touch and step voltages can occur in that area in the event of a single-phase-to-ground fault.

The existence of a GGS can be proved with simulations and field measurements and depends on several factors, among which, the value of the fault current and of the ground resistances of the interconnected ground-grids, as well as the type of neutral grounding.

Mathematical models presented in [19] show that the use of the Petersen coil in substation can positively impact the creation of a GGS.

Let us consider a MV network with the parameters of Table I, where the MV-LV substation ground-grids are interconnected by the metal sheath of the MV feeder cables. A single-phase-to-ground fault is assumed to occur at the 10th substation, involving one of the 13 identical MV lines.

TABLE I. PARAMETERS OF THE MV POWER GRID.

Rated voltage [kV]	20
Permissible touch voltage U_{TP} in the case of isolated-from-ground neutral [V]	220
Permissible touch voltage U_{TP} in the case of resonant grounded neutral [V]	75
Single-phase-to-ground fault current in the case of isolated-from-ground neutral [A]	400
Single-phase-to-ground fault current in the case of resonant grounded neutral [A]	50
Number of MV lines supplied by the same HV-MV station	13
Number of MV-LV substations per line	20
Distance between the substations [km]	0.3
MV cable	RG7H1OZR 15/20 kV
Cable description	Three-core cable with an unique metal sheath.
Rated cross-section [mm^2]	3x95
Series distributed resistance [Ω/km]	0.250
Conductor's diameter [mm]	11.6
Sheath series distributed resistance [Ω/km]	0.61
Sheath diameter [mm]	35
Distance between the phase wires [mm]	12
Average distance between a phase wire and the metal sheath [mm]	23
Shunt capacitance [μF/km]	0.28
Ground resistance of the substations [Ω]	20
Ground impedance of the HV-MV station [Ω]	0.1
Soil bulk resistivity [Ω.m]	100

If the neutral point of the MV network is isolated-from-ground the single-phase-to-ground fault current is 400 A and the GPR at the substations must be below 440 V (i.e., value of $2U_{Tp}$=2x220 V, per IEC 61936-1). Thanks to the interconnection of the ground-grids of the substations, the GPR, calculated as reported in [20], assumes the values shown in Fig. 10.

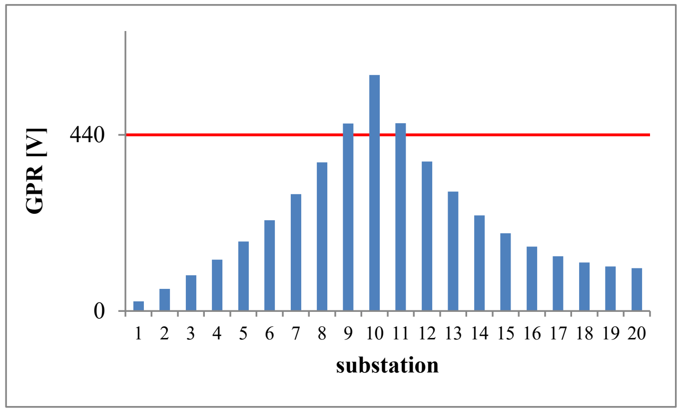

Fig. 10. GPR distribution in the case of neutral isolated-from-ground and fault at the 10th substation.

The faulted substation and the those closest to it, experience GPRs exceeding the permissible limit. In this case, touch and step voltage measurements must be performed to verify the effectiveness of the grounding system, in the presence of the interconnection between all the ground-grids. In these conditions, the interconnected ground-grids cannot be deemed to form a GGS: one of the major advantages of the GGS is not to have to perform touch and step voltages measurements, which may be challenging.

In the case of resonant grounding, the same network has a single-phase-to-ground fault current of 50 A, and the GPR at the substations must be below 150 V (i.e., $2U_{Tp}$=2x75V, per IEC 61936-1). In this case, thanks to the interconnection of the grounding systems of the substations, the GPR at each substation for the same fault location assumes the values shown in Fig. 11, which are all below the permissible limit; the interconnected system can be deemed to be a GGS.

The case above does show that the transition from isolated-from-ground to resonant grounded neutral may allow the formation of a GGS, and of the related inherent electrical safety, without costly improvement of the ground-grids.

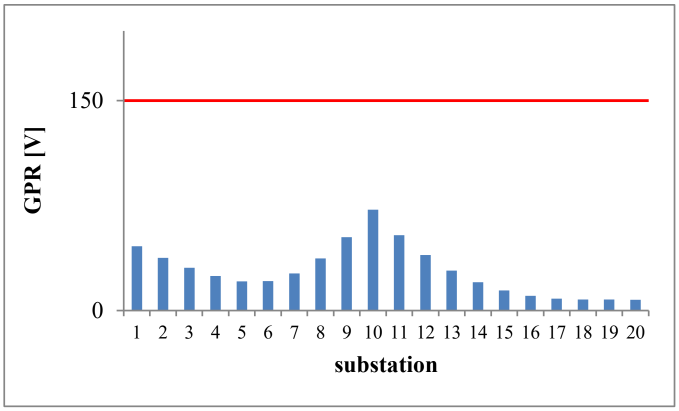

Fig. 11. GPR distribution in the case of resonant grounded neutral and fault at the 10th substation.

VII. CONCLUSIONS

This paper, based on [21], has discussed specific safety issues related to the use of the Petersen coil in MV networks, when reconfigurations of the type of neutral grounding of existing substations take place.

The authors have discussed the electrical safety challenges involved in the transition from isolated-from-ground to resonant-grounded neutral in medium voltage networks. This reconfiguration, dictated by new requirements for power quality to electric utilities by Regulatory Authorities, may lead to changes in the values of the ground-fault currents and fault clearing times, whose combination may render the system unsafe due to unacceptable touch voltages.

The authors have also proposed a procedure to assess if a ground-grid designed per the requirements of an isolated-from-ground system can be still considered safe in the new resonant-ground configuration, and vice versa. This procedure can also be used to pre-emptively size ground-grids in the design phase of substations.

A case study was presented that has shown how the transition from isolated-from-ground to resonant grounding neutral may allow the formation of a GGS, improving safety against electric shock.

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AUTHORS' CONTRIBUTION

The names of the authors are listed in alphabetic order. All authors gave an equal contribution in writing the final version of the paper.

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Massimo Mitolo (SM'03) received the PhD in electrical engineering from the University of Naples "Federico II," Napoli, Italy, in 1990. Dr. Mitolo is currently a Full Professor of electrical technology with the Irvine Valley College, Irvine, CA, USA. Dr. Mitolo has authored more than 100

journal papers and the books Electrical Safety of Low-Voltage Systems (McGraw-Hill, 2009) and Laboratory Manual for Introduction to Electronics: A Basic Approach (Pearson, 2013). His research interests include the analysis and grounding of power systems, and electrical safety engineering.
Dr. Mitolo is a registered Professional Engineer in the state of California and in Italy. He is active within the Industrial and Commercial Power Systems Department of the IEEE Industry Applications Society (IAS), where he is currently the Vice-Chair of Papers, the Chair of the Power Systems Analysis Subcommittee, and the Chair of the Grounding Subcommittee. He also serves as an Associate Editor for the IEEE IAS Transactions. Dr. Mitolo has received numerous recognitions and awards, among which are the 2012 IAS industrial & commercial power systems (I&CPS) Ralph H. Lee Department Prize Paper Award and the IEEE Region 6 2015 Outstanding Engineer Award.

Rossano Musca obtained his M.S. degree and his Ph.D. degree in Electrical Engineering in 2007 and 2010, respectively, from the University of Palermo, Italy. From 2011 to 2018 he was working with Busarello + Cott + Partner AG as responsible of the Dynamic Analysis module of NEPLAN. Since 2018 he is post doc research fellow at the Engineering Department of the University of Palermo. His current research interests include power systems design, frequency regulation and stability analysis.

Michele Tartaglia (SM'08) received the Laurea degree in electrical engineering from the Politecnico di Torino, Turin, Italy, in 1971. In 1973, he joined the Istituto Elettrotecnico Nazionale "Galileo Ferraris," Turin, where he carried out theoretical and experimental studies on breaking apparatus and computation of electromagnetic fields in nonlinear devices. From 1982 to 2010, he was an Associate Professor, and is currently a Full Professor with the Politecnico di Torino. He is also the scientific responsible of research contracts with public institutions and private companies, and is involved in European community projects. He has authored more than 110 scientific papers. His main research interests include the study of breaking apparatus, electromagnetic fields by means of analytical and numerical methods, mitigation of low-frequency magnetic fields, security in electrical power systems, and rational use of energy. Dr. Tartaglia is a member of the IEEE Industry Applications Society and the Federazione Italiana di Elettrotecnica, Elettronica, Automazione, Informatica, e Telecomunicazioni. He is also a member of the CIGRE Task Force Working Group 36.04.01 on Magnetic Field Mitigation Methods and the Technical Committee CT 106 on Human Exposure to Electromagnetic Fields of the Comitato Elettrotecnico Italiano. In 1977, he received the Bonavera Award for Electrical Engineering from the Accademia delle Scienze di Torino, Turin.

Gaetano Zizzo (SM'17) is Assistant Professor of Electrical Power Systems at the University of Palermo, Italy, where he obtained his M.S. degree in 2002 and his Ph.D. degree in Electrical Engineering in 2006. Since 2006 he works at the Engineering Department of the same university. In 2017 he was elected Senior Member IEEE as a member of the Industry Application Society. He is involved in the activities of the IEEE Standard Association. His current research interests include electrical safety, power systems design, management, and optimization, smart grids and stability analysis.