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Temporary overvoltages due to ground faults in MV networks

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***Abstract*--The paper deals with the temporary overvoltages that build up in radial MV distribution networks following the inception of a 1-phase-to-ground fault (1-Φ -to-Gr). For extended cable/overhead MV distribution networks with ungrounded neutral, in case of low resistance faults at critical stretch of overhead lines, in [1] it has been evidenced that the temporary overvoltages on healthy phases can be very large, much higher than √3 p.u. (up to 3.5 p.u.). Fault currents can reach twice the value calculated with simplified methods, i.e. neglecting series impedances. In this paper the study is extended to MV networks with neutral grounded by both Petersen coil and compensating impedance (Petersen coil with a resistance in parallel), in normal operation and under contingency, i. e. in case of whole or partial loss of the compensating impedance. It is demonstrated that the presence of Petersen coil, stand alone or in parallel with a grounding resistance, drastically reduces the above temporary overvoltages at values not greater than 1.7-1.8 p.u. Application of simple derived formulas to the case of partial loss of the compensating neutral impedance show that overvoltages can be reduced at 1.8÷2.2 p.u., also in case of MV network having very high capacitive fault current (e.g. ≥300 A) and long overhead lines. An ATP case study on an existing 20kV large Enel-Distribuzione network reported in the paper confirm that the theorical predicted overvoltages are in the above mentioned range, and that the technical solutions adopted by Enel-Distribuzione [9-15] are able to limit in most cases the overvoltages at values not greater than 1.85 p.u..**

***Index Terms*—MV Networks, Neutral Grounding, Ground Fault, Temporary Overvoltages, Compensating Neutral impedance, Petersen Coil.**

I. Nomenclature

E	MV supply voltage
R_F	Fault resistance
C_{0N}	MV network zero-sequence capacitance
X_n, R_n	Neutral grounding reactance (Petersen coil) and parallel resistance
R_{1fl}, R_{0fl}, X_{1fl}, X_{0fl}	Positive-sequence and zero-sequence series resistances and reactances of the faulted line up to fault location
$\mathbf{E}_{1F}$, $\mathbf{E}_{2F}$, $\mathbf{E}_{0F}$,	Positive-, negative-, and zero-sequence voltages at fault location
$\mathbf{E}_{1B}$, $\mathbf{E}_{2B}$, $\mathbf{E}_{0B}$,	Positive-, negative-, and zero-sequence voltages at MV supply busbars
$\mathbf{E}_{TB}$	T-phase voltage at MV supply busbars
$\mathbf{I}_F$, $\mathbf{I}_{0F}$	Fault current, zero-sequence fault current (=$\mathbf{I}_F/3$)
$\mathbf{I}_{CF}$, $\mathbf{I}_{0C}$	Total and zero-sequence capacitive fault current (neglecting series impedances: $I_{CF}=3I_{0C}=3\omega C_{0N}E$)
E_{max}	Maximum overvoltage on healthy phases

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II. Introduction

European MV (3.3–33 kV) distribution networks have several topologies, but radial operation with the provision for back-feed is widespread. In comparison to meshed operation, this practice allows simpler control, operation and cheaper system protection but, on the other hand, it decreases the security of supply for MV customers and MV/LV distribution networks. Neutral grounding practices in Europe differ widely on a national basis (and sometimes within the same country), mainly due to historical and economical factors. Solutions adopted by Distributors varies from solidly grounded neutral (e.g. UK) to ungrounded neutral (e.g. parts of Italy and of Finland and Spain), and include all kinds of impedance grounding or resonant grounding. In the past Italy Enel-Distribuzione operated their MV networks with ungrounded neutral, but a complete conversion to compensated grounding will be ended in the mid-term.

Line series impedances are generally neglected in calculations of 1-Φ-to-Gr fault currents and overvoltages in MV networks with ungrounded or high impedance-grounded neutral. This approximation was justified when dealing with small distribution networks, consisting of mostly overhead lines. Today, MV networks can be relatively large (200-400 km of aggregate line length) and/or consist mostly of cables, with long overhead and mixed cable/overhead lines in suburban and rural areas. For such networks and in case of ungrounded neutral, disregarding line series impedances can lead to unacceptable underestimation of 1-Φ-to-Gr fault currents and overvoltages. The above simplification yields maximum healthy phase temporary overvoltages just a little larger than the phase-to-phase nominal voltage (√3 p.u. to ground), i.e. 1.823 p.u. with ungrounded neutral [2].

On the contrary, larger overvoltages are actually recorded in real networks: in case of 1-Φ-to-Gr fault with ungrounded neutral, critical but credible network configurations are liable to experience overvoltages over 3 p.u. on the healthy phases.

In the present paper will be discussed the MV network behavior with ungrounded and impedance grounded neutral.

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III. Temporary overvoltages in extended MV distribution networks with ungrounded neutral

In order to avoid underestimating 1-Φ-to-Gr fault current and attendant temporary overvoltages in ungrounded neutral networks, the longitudinal impedance of the faulted line must be taken into account [3,4,5].

During 1-Φ-to-Gr fault the well known full or partial resonance between zero sequence and twice positive sequence Thevenin reactances, causing high currents and overvoltages, has been pointed out in the developing stage of not solidly grounded HV transmission and subtransmission systems [5,6].

This phenomenon can also happen in extended non-solidly grounded MV networks. Let us consider the MV distribution network shown in Fig. 1, consisting of many overhead/cable radial lines originating from the MV busbars (B) of the Primary Substation (PS), which is supplied by a HV/MV step-down transformer with ungrounded neutral (switch S open in Fig 1a). The formula of the 1-Φ-to-Gr fault current at receiving end of a radial line, $\mathbf{I}_F$, and of the maximum healthy phase overvoltage, $\mathbf{E}_{TB}$, can be obtained as [1]:

$$\mathbf{I}_F = \frac{3\mathbf{E}}{2R_{1fl} + R_{0fl} + 3R_F + j\left(2X_{1fl} + X_{0fl} - \frac{1}{\omega C_{oN}}\right)} \qquad (1)$$

$$\mathbf{E}_{TB} = \left[\frac{-\frac{1}{j\omega C_{0N}}}{2R_{1fl} + R_{0fl} + 3R_F + j\left(2X_{1fl} + X_{0fl} - \frac{1}{\omega C_{0N}}\right)} + (1\angle 120°)\right]\mathbf{E} \qquad (2)$$

When $2X_{1fl}+X_{ofl}-1/(\omega C_{oN}) = 0$, I_F and E_{TB} reach maximum values. This can happen in case of high values of C_{oN} and X_{ofl}, i. e. when the fault occurs at the end of a long radial overhead line (high X_{ofl}) belonging to an extended MV network (high C_{oN}).

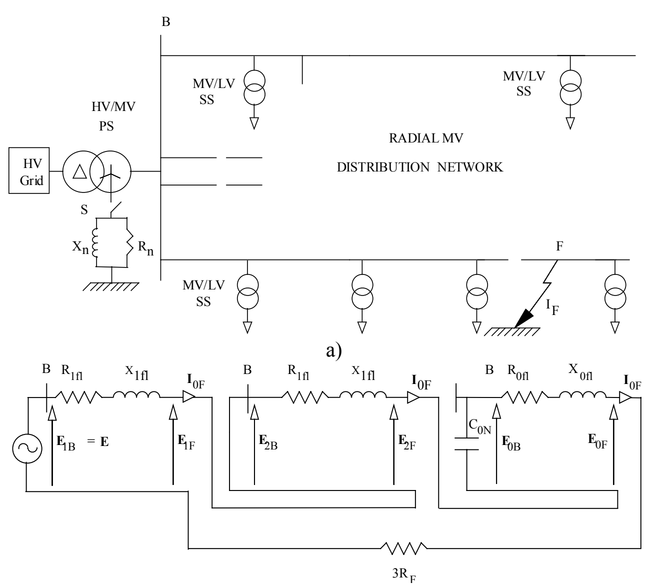


Fig. 1. Radial MV distribution network: (a) single-line diagram; (b) Connection of sequence networks in case of 1-Φ-to-Gr fault.

Overvoltages of 2.5-3.5 p.u. may occur in low resistance fault to ground in extended MV network with ungrounded neutral [1].

IV. MV networks with compensated neutral

A. Full compensation

In Fig.1 let us consider the switch S closed, so that the neutral is connected to ground by the Petersen coil, X_n, and by the parallel resistance, R_n. X_n is chosen equal to $1/(3\,\omega C_{oN})$ [4,5,6,7,8] while R_n is set in such a way to limit the resistive fault current at some tens of A (Enel-Distribuzione in Italy and EDF in France limit the resistive current to about 20-40A).

With the same approximations introduced in § III, and assuming a perfect compensation of the zero-sequence network capacitances, in case of 1-Φ-to-Gr fault at the end of a radial line, solution of the circuit in Fig. 2 yields the following zero sequence voltages at fault point (3) and at supply busbars (4):

$$\mathbf{E}_{0F} = -\frac{3R_n + R_{0fl} + jX_{0fl}}{2R_{1fl} + R_{0fl} + 3R_n + 3R_F + j(2X_{1fl} + X_{0fl})}\mathbf{E} \qquad (3)$$

$$\mathbf{E}_{0B} = -\frac{-3R_n}{2R_{1fl} + R_{0fl} + 3R_n + 3R_F + j(2X_{1fl} + X_{0fl})}\mathbf{E} \qquad (4)$$

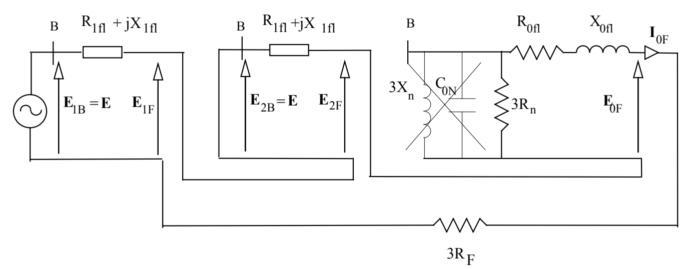


Fig. 2. Sequence networks connection in case of radial MV network with compensated neutral (100% compensation).

From (3) and (4) it follows that for bolted faults (R_F=0) the amplitudes of $\mathbf{E}_{0B}$ and $\mathbf{E}_{0F}$ are less than 1 p.u.; since the neutral resistance R_n is prevalent, both voltages are phase shifted by about 180° with respect to the phase pre-fault voltage $\mathbf{E}$. Furthermore, as $\mathbf{E}_{1B}$, $\mathbf{E}_{1F}$, $\mathbf{E}_{2B}$, $\mathbf{E}_{2F}$ are very small, it can be concluded that the maximum overvoltages on healthy phases are not greater than √3 p.u. for every fault location.

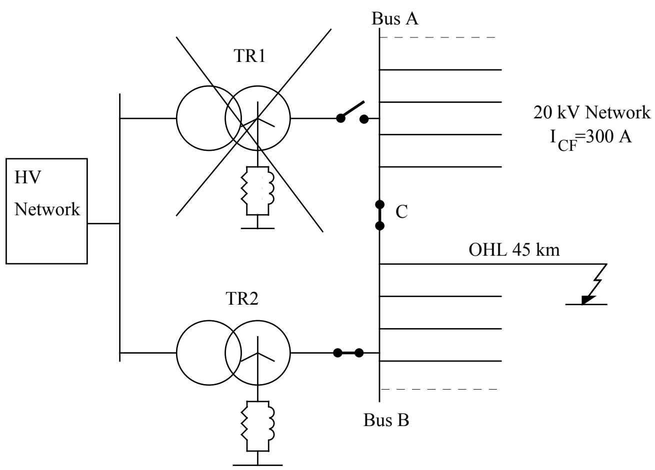
B. Partial compensation

If the Petersen coil ($X_n=\omega L_n$) is not tuned to the zero sequence network capacitance, C_{oN}, i.e. $B_n=1/(3X_n) = K/(\omega C_{oN})$ with $0 \le K \le 1$, the following expressions are arrived at:

$$
\begin{cases}
\mathbf{I}_F = -\dfrac{3\,\mathbf{E}}{2(R_{1fl}+jX_{1fl})+(R_{0fl}+X_{0fl})+Z_{0B}+3R_F} \\
\mathbf{E}_{OB} = -\mathbf{Z}_{0B}\ \mathbf{I}_F \\
\mathbf{E}_{Bmax} = \mathbf{E}+(1\angle 120°)\ \mathbf{E}_{0B} \\
\mathbf{Z}_{0B} = \dfrac{3R_n}{1+j\,3R_n\omega C_{OB}(1-K)}
\end{cases}
\qquad (5)
$$

By using formula (5) the curves of maximum overvoltage, E_{max}, and the fault current, I_F, versus K, with assigned values of R_F, R_n and length of the faulty overhead line, can be easily obtained.

For example let us consider the case of 20 kV radial distribution network sketched in Fig. 3, with a relatively large capacitive fault current of I_{CF}=300 A, and an 1-Φ-to-Gr fault at the end of an uniform 45 km long overhead line.



Primary faulty overhead line electrical constants: r_1+j x_1=0.23+j 0.35 Ω/km; r_0+j x_0=0.376+j 1.48 Ω/km, c_0=4.5 nF/km)

Fig.3. Typical 20 distribution network with two radial MV subnetworks

Fig. 4 shows the curves of maximum healthy phase overvoltage at PS busbar and of 1-Φ-to-Gr fault current, versus compensation degree K, with and without neutral resistance R_n, for some significant values of fault resistance, R_F.

Let us consider the following very severe contingency case: loss of a transformer with one compensating impedance already out of order and subsequent parallel operation of bus-A and B.

This conditions match the case of K=0.5 for the considered network. From Fig. 4a, when only the Petersen coil is installed and for a credible fault resistance, R_F=10Ω, the maximum healthy phase overvoltage is contained at 2.4 p.u. and the fault current is 223 A. When the resistance R_n is installed in parallel with Petersen coil the maximum overvoltage is still further kept down to 2.19 p.u. and the fault current decreases somewhat to a value of 199 A.

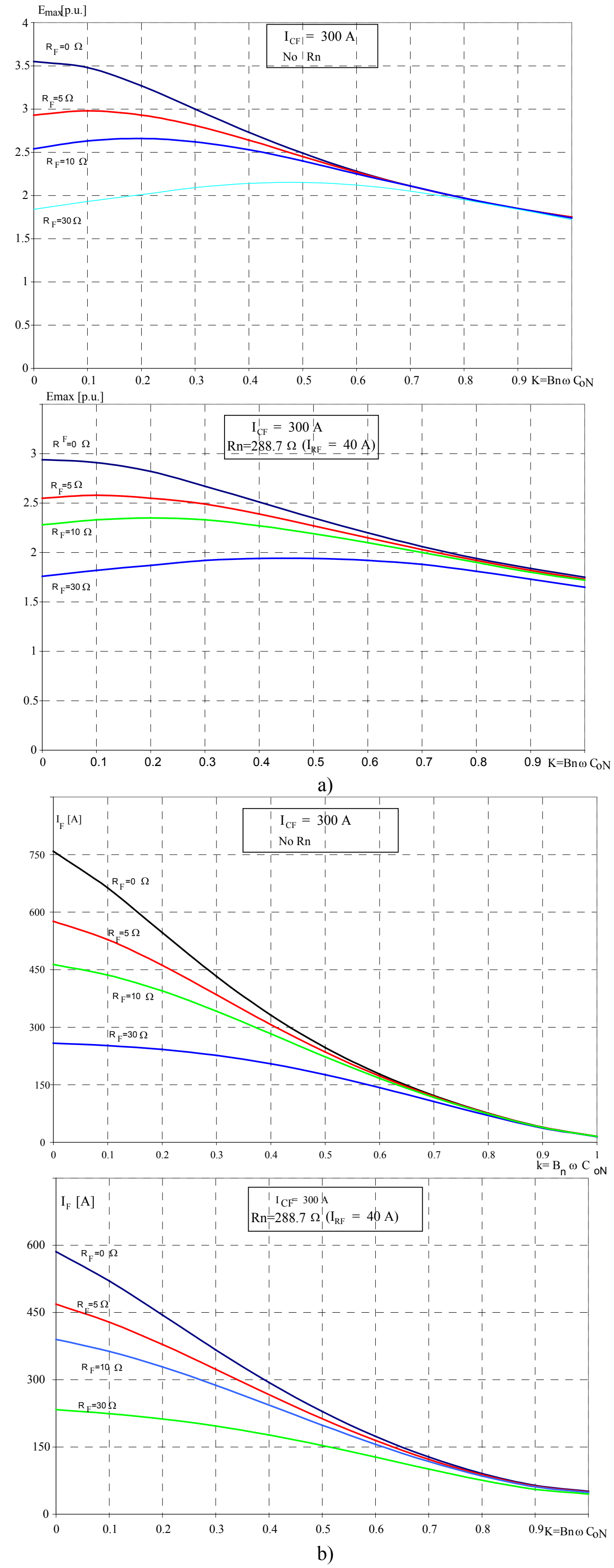


Fig. 4. 1-Φ-to-Gr fault at the end of an uniform 45 km long overhead line of 20kV network with a I_{CF}=300A: a) Maximum healthy phase overvoltage at busbars versus compensation degree K; b) 1-Φ-to-Gr fault current versus compensation degree K.

IV. Application to an Existing Extended Mixed Overhead-Cable Line Italian Network

The usual Enel-Distribuzione practice is to split the whole radial MV network (Fig. 5.a), originating from the MV-PS, in two subnetworks fed by two distinct 20 kV busbars, called Red and Green busbars. These busbars are connected to two HV/MV transformers and in normal conditions they are kept separated, while during contingencies they can be operated in parallel by closing the parallel-busbar circuit breaker (CB in Fig.5.a). The Enel-Distribuzione standardised transformers have both HV and MV wye-connected and the neutral of the MV winding can be operated isolated or grounded by an impedance. In the past ENEL-Distribution operated the neutral of the MV network ungrounded, but a complete conversion to compensated grounding is ongoing: today more than 60% of the Enel-Distribuzione MV networks have the neutral grounded by compensating impedance.

According to the specific MV network the neutral grounding is obtained by applying different schemes, using simple resistors, or Petersen coils with a parallel resistance (Fig. 5.b). Petersen coil can be either an off-load adjustable inductance or a variable inductance, able to automatically tune itself with the zero sequence network capacitance, to face the prospective different MV network configurations [9].

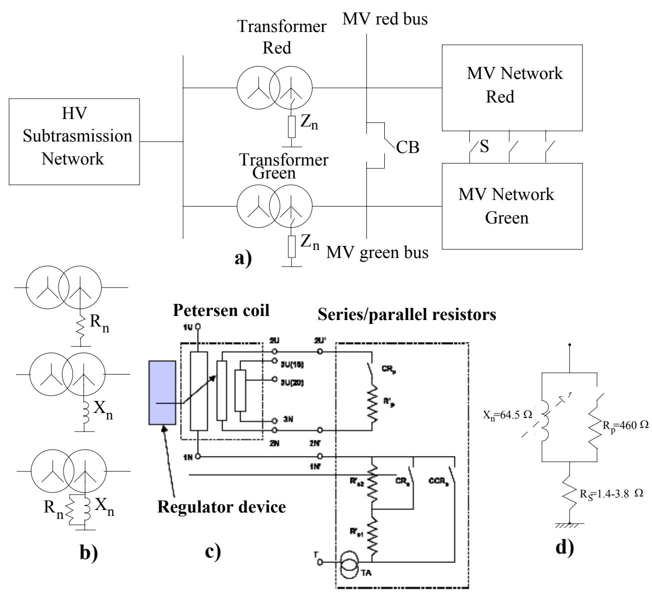


Fig. 5. a) Scheme of Enel-Distribuzione PS and MV network; b) Connection of neutral MV winding transformers; c) Equivalent circuit of the grounding system impedance

Furthermore Enel-Distribuzione has in depth studied, designed and fine-tuned different MV neutral grounding systems in order to obtain satisfactory operation flexibility in case of outage of the HV/MV transformer and/or of the neutral compensating impedance.

As case study the existing ENEL-Distribuzione Italian 20kV-50 Hz network shown in Fig. 6 has been considered. The 20 kV network has an overall line length of 322.8 km, 197.1 km of which are overhead line and 125.7 km are cable lines. The capacitive 1-Φ-to-Gr fault current of the network is 320 A, 180 A contributed by the Red network, which has 186 km (73.5%) of overhead lines. The main characteristics of the 20 kV network are summarised in Table I.

The scheme of the neutral compensating impedance according to Enel-Distribuzione in case of variable Petersen coil is reported in Fig. 5.c. The equivalent circuit of the neutral grounding system considered for the studied 20kV network is reported in Fig. 5.d: for the Red transformer it is assumed X_n=64.5 Ω and R_p=460 Ω.

The complete HV/MV system of Fig.6 has thus simulated by ATP program in order to evaluate the temporary overvoltages which may arise following 1-Φ-to-Gr fault in the 20 kV network, in case of either ungrounded or compensated neutral, during normal operation and contingencies, as outage of the green neutral compensating impedance.

The fault to ground has been simulated at the end of a mixed overhead-cable 44 km long line, 36 km of which are made of overhead line and 8 km of cable line (Fig. 6). Fault resistance has been varied in the range 0-10 Ω.

For the studied 20 kV distribution network the main results reported in Tab. II point out:

- In case of operation with separated PS-MV busbars and 20kV ungrounded neutral subnetworks, or in contingency case, i.e. in case of Green compensating impedance outage, the current $I_{1\text{-}\Phi\text{-to-}Gr}$ is in the range of 213÷224 A, i.e. 12÷20% greater than the value calculated neglecting all series impedances; the overvoltages are 2.18 p.u., (case N.1 of Tab. II);
- With PS-MV busbars operated in parallel (one HV/MV transformer being out of service) and with ungrounded neutral of the 20 kV subnetworks, the fault currents are in the range of 383÷461A, i.e. 14% and 37 % greater than the value calculated neglecting all series impedances. The overvoltages on healthy phases reach 2.3÷2.46 p.u. (case N.2 of Tab. II);
- In normal operation, when Petersen coil is applied, with or without parallel resistance, the overvoltages are reduced to values not greater than 1.82 p.u. (cases N.3 and N.4 of Tab. II); I_F=6÷30 A.
- In case of loss of one HV/MV transformer, with busbars operated in parallel and with only Red-neutral compensating impedance in operation, the overvoltages are 2.03-2.07 p.u. (cases N.5 and N.6 of Tab. II);
- Petersen coil of variable value and oversized, so as to compensate also a good part of the Green zero sequence network capacitance, allows to contain the overvoltages at value in the range of. 1.83-1.85 (cases N.7 and N.8 of Tab II).

Among the different systems designed by Enel-Distribuzione for MV networks neutral grounding [9-15], those ones concerning the extended MV networks, i.e. with high fault to ground capacitive current (100-480 A), are reported in Fig.7.

Scheme in Fig. 7.a is achieved by using a fixed reactor and a parallel resistor: it is applied for 20kV network having a capacitive fault to ground current in the range of 100A-200A. The parallel resistance has a value liable to contain the resistive fault current in the range of 28-36 A.

5

Table I
MAIN SIGNIFICANT CHARACTERISTICS OF THE ENEL-DISTRIBUTION ITALIAN 20KV-50 HZ NETWORK SHOWN IN FIG. 6

20 kV Subnetwork	PS Transformers	Total line length [km]	Overhead line length [km]	Cable line length [km]	Zero sequence network capacitance, C_{oN} [nF]	I_{CF} *) [A]
Red	120/20 kV N_n=40 MVA;V_{sc}=13%;	253	186	67	16480 nF	180
Green	120/20 kV N_n=40 MVA;V_{sc}=13%	69.8	11.1	58.7	13000 nF	141

*) $I_{CF} = 3\ \omega\ C_{oN}\ E_n$

Table II

MAIN RESULTS FOR THE CASE OF A 1-Φ -TO-GR FAULT AT THE RECEIVING END OF A 44 KM MIXED-OVERHEAD-CABLE LINE OF THE 20 KV NETWORK OF IN FIG. 6

Case N.	Red and Green bus operation	Neutral condition	Compensating impedance	Fault resistance $R_F[\Omega]$	$I_{1\phi-to-Gr}$ [A]	E_{oB} [p.u.]	E_{max} [p.u]	I_{Xn} [A]	I_{Rp} [A]
1	Separated	Isolated	_	R_F=0 Ω R_F=5 Ω R_F=10 Ω	224 220 213	1.26 1.24 1.20	2.18 2.18 2.18	-	-
2	Parallel connected	Isolated	_	R_F=0 Ω R_F=5 Ω R_F=10 Ω	461 422 383	1.46 1.33 1.21	2.46 2.38 2.28	-	-
3	Separated	Connected to ground by means of:	X_{nRED}= 64 Ω X_{nGREEN} in service	R_F=0 Ω R_F=5 Ω R_F=10 Ω	6.0 6.0 6.0	1.02 1.02 1.02	1.82 1.81 1.82	184 184 184	-
4	Separated	Connected to ground by means of:	X_{nRED}= 64 Ω R_p = 460 Ω Z_{nGREEN} in service	R_F=0 Ω R_F=5 Ω R_F=10 Ω	29.5 29.5 28.8	1.00 0.99 0.98	1.82 1.81 1.80	180 178 176	25.0 24.7 24.4
5	Parallel connected	Connected to ground by means of:	X_{nRED}= 64 Ω Z_{nGREEN} out of service	R_F=0 Ω R_F=5 Ω R_F=10 Ω	161 160 157	1.20 1.18 1.16	2.07 2.07 2.07	217 214 210	_
6	Parallel connected	Connected to ground by means of:	X_{nRED}= 64 Ω R_p = 460 Ω Z_{nGREEN} out of service	R_F=0 Ω R_F=5 Ω R_F=10 Ω	162 158 153	1.16 1.13 1.10	2.04 2.04 2.03	210 204 199	29.1 28.4 27.5
7	Parallel connected	Connected to ground by means of:	X_{nRED}=38.5 Ω *) Z_{nGREEN} out of service	R_F=0 Ω R_F=5 Ω R_F=10 Ω	26.0 25.8 25.7	1.03 1.02 1.02	1.85 1.85 1.85	310 307 305	_
8	Parallel connected	Connected to ground by means of:	X_{nRED}=38.5 Ω *) R_p = 460 Ω Z_{nGREEN} out of service	R_F=0 Ω R_F=5 Ω R_F=10 Ω	44.5 43.8 43.1	1.00 0.99 0.98	1.84 1.84 1.83	301 296 291	25.2 24.8 24.4

*) Petersen coil with 300 A rated current

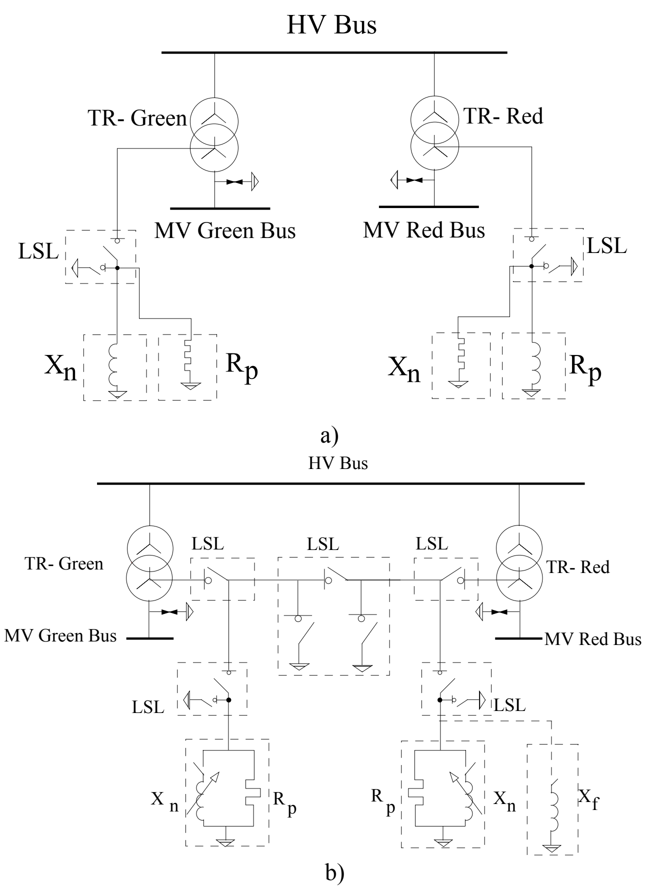


Fig. 7. Two among the different schemes applied by Enel-Distribuzione to grounding the MV distribution networks

Scheme in Fig. 7.b) is applied in case of networks with a capacitive ground fault current up to 300A. The compensating impedance is made up of a resistor in parallel to a variable inductance that automatically tunes itself to the zero sequence capacitance of the network. This scheme is very flexible because by switching the load-break switches it allows to connect each compensating impedance at any neutral transformer, or it allows isolating one or both transformer neutrals, by efficiently facing the outage of transformers or compensating impedance.

It should be noticed that when these schemes are applied, in case of loss of the neutral resistor R_n, the control system automatically brings about the Petersen coil disconnection, and the MV network come back to the ungrounded system: for this reason the cases N. 3, 5 and 7 cannot verify for MV Enel-Distribution networks.

Furthermore, in MV with a capacitive ground fault current up to 480 A Enel-Distribuzione installs a fixed reactor in parallel to the variable main one, as indicated in Fig.7.b

The solutions adopted by Enel-Distribuzione with the standardised values of reactors and resistors allow to limit the temporary overvoltages, caused by low resistance fault to ground at end of long overhead MV lines, at value not greater than of 2.0-2.1, and at value not greater than 1.8-1.85 p.u. when the scheme 7.b is applied. This latter is just the case N.7 and N. 8 reported in Tab. II.

V. CONCLUSIONS

The paper dealt with the temporary overvoltages and fault current following 1-Φ-to-Gr faults in extended, mixed cable/overhead line, radial MV networks.

For networks with ungrounded neutral, the 1-Φ-to-Gr faults at the receiving end of long overhead lines can cause abnormal overvoltages (2.5 –3 p.u.), especially at PS busbars and in healthy lines.

The paper shows that, with compensated neutral, the above phenomena are drastically suppressed (E_{max}≤1.73 p.u.) as long as the compensation degree is near 100%. The same phenomena highlighted for ungrounded neutral can happen only in very unlikely cases of total failure of the neutral grounding system.

In more credible, but still very severe, contingency case of partial failure of the MV neutral grounding in a PS the overvoltages are greater than 1.73 p.u. but in the range of 1.8.÷2.2 p.u..

The above values predicted by simple proposed formulas are confirmed by a detailed ATP simulation of an extended 20kV network of Enel-Distribuzione.

Technical solutions adopted by Enel-Distribuzione to grounding the neutral of MV networks are able to limit in most cases the overvoltages at values not greater than 1.85 p.u..

Experimental tests are planned on large Enel-Distribuzione MV distribution networks.

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