ABNORMAL GROUND FAULT OVERVOLTAGES IN MV NETWORKS: ANALYSES AND EXPERIMENTAL TESTS

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ABSTRACT

ENEL DISTRIBUZIONE mainly operates it's MV distribution networks with compensated neutral, obtaining an excellent improvement of quality of supply without any problem for the fault selection. Instead, in many other European countries where ENEL is present, different ways of neutral grounding are used, in particular earthing resistances, assuming that this solution would allow an easier selection of the faulty line (phase to earth fault selection) and a reduction of possible Temporary Overvoltages (TOV), especially on mainly cable network

The paper investigate TOV affecting the healthy phases of a radial MV distribution networks operated with non-effectively grounded neutral originated by a single phase-to-ground fault. Theoretical analysis carried out for several network configurations and fault parameters proved that worst-case TOVs can reach 3.5 p.u. phase-to-ground with ungrounded neutral and 1.8 p.u. with compensated neutral (pure reactance or Petersen coil in parallel with a grounding resistance).

The theoretical results, obtained by ATP code, have been fully confirmed by a full-size experimental real field tests performed on the ENEL DISTRIBUZIONE network, both with insulated neutral, stand-alone Petersen coil and Petersen coil with permanent parallel resistance.

The study confirms that extended radial MV networks with insulated neutral may experiment 'abnormal' TOVs for certain ground faults, and that neutral compensation has a remarkable effectiveness in suppressing the phenomenon, similar to low earthing resistors, in addition to a drastic reduction of fault currents in earthing plants.

INTRODUCTION

Advantages and drawbacks of different neutral operations of MV distribution networks are under discussion from tens of the years in the world. ENEL DISTRIBUZIONE, 10 years ago decided to change the operation of the neutral point of its MV networks from ungrounded to compensated, the process being now more than 60% completed. Viceversa, in many other European countries different neutral groundings are used, in particular pure earthing resistors, to improve protection sensitivity and to contain the temporary overvoltages (TOV) on healthy phases in case of a phase-to-ground faults (1-Φ-to-Gr), especially on mainly cable networks.

In calculations of 1-Φ-to-Gr fault currents and voltages in MV networks, with ungrounded or high impedance-grounded neutral, line series impedances are generally neglected yielding healthy phase TOVs to ground around √3 p.u.. This approximation is justified when dealing with small distribution networks, consisting of mostly overhead lines. Today, MV networks can be relatively extended (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 associated overvoltages [1], [2]. 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 [3]. On the contrary, higher overvoltages are actually recorded in real networks: in case of 1-Φ-to-Gr fault with ungrounded neutral, critical but credible network configurations may experience healthy phase TOVs over 3 p.u..

The paper, first, presents a brief explanation of the phenomena causing the high TOV following 1-Φ-to-Gr fault in MV networks, after reports the results of the ATP analyses performed on the 20 kV-Udine Rotonda ENEL DISTRIBUZIONE network and, finally, shows the preliminary results of the experimental test performed on the mentioned Udine Rotonda network compared with the ATP ones.

1-Φ-TO-GR FAULT CURRENT AND OVERVOLTAGES IN MV DISTRIBUTION NETWORKS WITH DIFFERENT NEUTRAL PRACTICE GROUNDINGS

In order to avoid underestimating 1-Φ-to-Gr fault current and attendant TOVs in ungrounded neutral networks, the longitudinal impedance of the faulted line should be taken into account [1],[2],[4],[5].

During 1-Φ-to-Gr faults occurrence the 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 transmission and subtransmission networks [5],[6]. This phenomenon can indeed happen also in extended non-solidly grounded MV networks, as below shown[1].

MV network with ungrounded neutral

Referring to network in Figure 1, consisting in overhead/cable radial lines originating from the MV busbars (B) of the HV/MV (Primary) Substation (PS), fed by a HV/MV transformer with ungrounded neutral (switch S open), the 1-Φ-to-Gr fault current at the end of a radial line, I_F, and the maximum PS healthy phase TOV, E_{Bmax}, are given by (1) and (2), respectively, [1]:

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

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

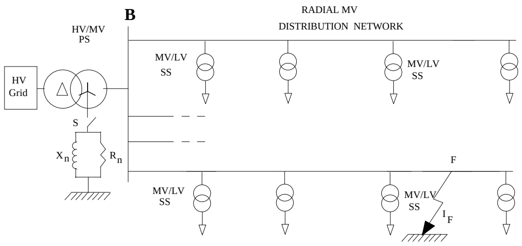

Figure 1-a: radial MV distribution network - single-line diagram

When $2X_{1fl}+X_{ofl}-1/(\omega C_{0N})=0$, I_F and E_{TB} reach maximum values. This can happen in case of high values of both C_{0N} and X_{0fl}, i.e. when fault occurs at the end of a long radial overhead line (high X_{ofl}) belonging to an extended MV network (high C_{0N}). Overvoltages of 2.5÷3.5 p.u. may actually occur for low fault resistance in extended ungrounded neutral MV network [1].

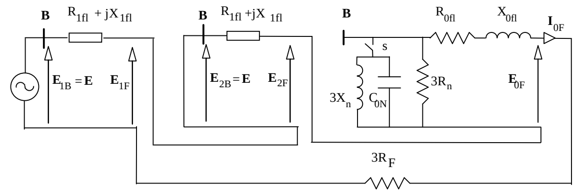

Figure 1-b: radial MV distribution network - sequence networks in case of 1-Φ-to-Gr fault

MV network with fully compensated neutral

In Figure 1, with the switch S closed, the neutral is connected to ground by the Petersen coil, X_n, and by the parallel resistance, R_n. X_n is chosen ~$1/(3\omega C_{oN})$ [5],[6],[7],[8] while R_n generates a resistive fault current of about 35 A (for wattmetric protections and FPIs).
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 Figure 1-b yields the following zero sequence voltages at fault point (3) and at supply busbars (4):

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

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

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

MV network with partially compensated neutral

If Petersen coil ($X_n=\omega L_n$) is not tuned to the zero sequence network capacitance, C_{oN}, introducing the neutral compensation degree K as $K=\omega C_{oN}/(3X_n)$ ($0 \le K \le 1$), the following expressions are derived:

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

Formula (1) to (5) were applied to the 20 kV radial network sketched of Figure 2, assuming a relatively large capacitive fault current I_{CF} ~ 300 A (i.e. about 80 km of cable lines) and occurrence of the 1-Φ-to-Gr fault at the end of a 45 km long overhead line.
Curves of Figures 3 show the maximum overvoltage, E_{max}, versus compensation degree K, with two assigned values of R_n, ∞ Ω and 288.7 Ω (i.e. I_{RF}=40 A at

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1 R_F: Fault resistance
C_{0N}: MV network zero-sequence capacitance
X_n, R_n: Neutral grounding reactance (Petersen coil) and parallel resistance
$\mathbf{Z}_{1fl}$, $\mathbf{Z}_{0fl}$: Positive-sequence and zero-sequence series impedances of the faulted line, up to fault location
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
E: MV supply voltage
$\mathbf{I}_F$, $\mathbf{I}_{0F}$: Fault and 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

Vn=20/√3 kV) and 5 different values of the fault resistance R_F (0-5-10-20-30 Ω).

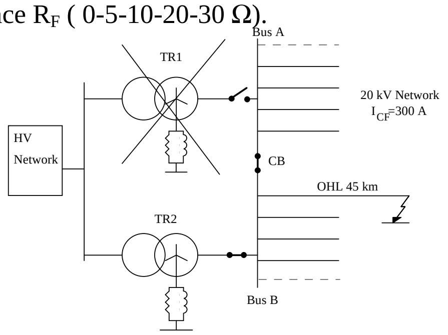


Figure 2: MV radial distribution network [2]

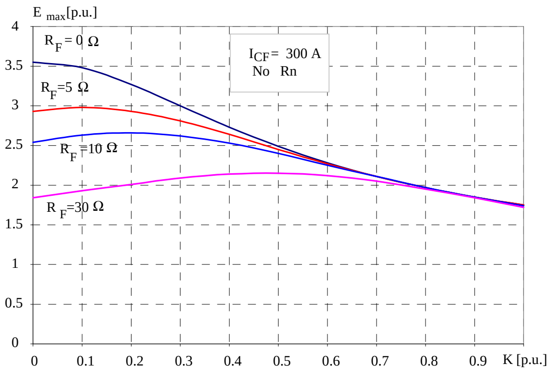


Figure 3a: 1-Φ-to-Gr fault at the end of an uniform 45 km long overhead line of 20kV network with a I_{CF}=300A. Maximum healthy phase TOV at busbars versus compensation degree K, in case of $R_n=\infty$

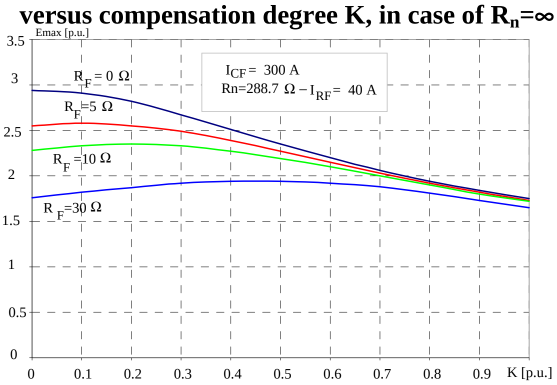


Figure 3b: 1-Φ-to-Gr fault at the end of an uniform 45 km long overhead line of 20kV network with a I_{CF}=300A. Maximum healthy phase TOV at busbars versus compensation degree K, in case of Rn=288.7 Ω

Let us examine three significant cases (R_n=0 Ω):

- K=0 (network with ungrounded neutral): TOV reaches 3.5 p.u. in case of bolted fault; it is 2.9 p.u. with R_F=5 Ω and it is still 2.55 p.u. in case of a relatively high fault resistance, R_F=10 Ω, of the MV/LV (Secondary) Substation (SS);
- K=1 (full compensation of C_{oN}); TOVs are not greater than 1.8 p.u. for each value of fault resistance;

2 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)

- K=0.5, e.g., a very severe, but still credible multiple contingency: loss of an HV/MV transformer with one compensating impedance already out of service and subsequent parallel operation of busses A and B [3]. In this case the maximum TOVs are still high, in the range of 2.2÷2.5 p.u., but significantly lower than the ones occurring with ungrounded neutral (2.5÷3.6 p.u.).

When a resistance is in parallel with Petersen coil TOVs are lower than in the case of ungrounded neutral, but can still be high (2.3÷2.9 p.u., 2.4÷2.5 p.u and 1.6÷1.75 p.u for K=0, K=0.5 e K=1, respectively) despite the neutral resistance R_n=288.7 Ω with ungrounded neutral or with low compensation of C_{0N} (Figure 3b).

For ungrounded neutral (K=0) formula (5) yields a 1-Φ-to-Gr fault current significantly higher than the value obtained by disregarding the series impedances. I_F is actually 2.5, 1.96, and 1.52 times I_{CF} (300A), for R_F=0, 5 and 10 Ω, respectively. Furthermore, even installing a stand alone neutral resistor R_N=288.7 Ω, I_F is still higher than I_{CF}, i.e. 1.97, 1.52 and 1.27 times I_{CF} for R_F=0, 5 and 10 Ω.

APPLICATION TO AN EXISTING EXTENDED MIXED OVERHEAD-CABLE LINE ITALIAN NETWORK

The MV ENEL distribution networks and its practice

The usual ENEL DISTRIBUZIONE practice is to operate the PS MV network radially and with separate busbars (Red and Green busbars, Figure 2). Bus coupler (CB) is normally open (closed only with one HV/MV TR disconnected). HV/MV transformers are Yyn0; TRs and MV neutral windings are designed for connection of an impedance.

According to features of MV network, the neutral grounding is obtained by applying different schemes, using simple resistors, or Petersen coils (off-load adjustable inductance or an automatic tunable inductance) with a parallel resistance (Figure 4) [9]. A further off-load fixed coil may be installed in parallel to an automatic tunable one. An intentional resistor is always present for wattmetric protections and FPIs; a pure Petersen coil, therefore with a resultant active current due only to the losses of coil itself and of the earthing transformer (HV/MV TR or an intentional one), is not foreseen in ENEL solutions.

All the solutions have been defined in order to obtain satisfactory operation flexibility in case of outage of the HV/MV transformer and/or of the neutral compensating impedance and includes networks up to I_{CF} = 500 A [9], [10], [11], [12], [13]. In particular, the scheme adopted

3 In ENEL DISTRIBUZIONE networks this can be considered a very rare situation, as, in this contingency, part of MV network would be supply from other adjacent PS and spare Petersen (tunable or fixed ones are are available) would be installed in 2÷3 days. Finally, Petersen coils are connected to PS MV busbars.

for networks with I_{CF}=300÷480 A is shown in Figure 5.
The connection schemes are very flexible because, by switching the 1-Φ switch-disconnectors, 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.

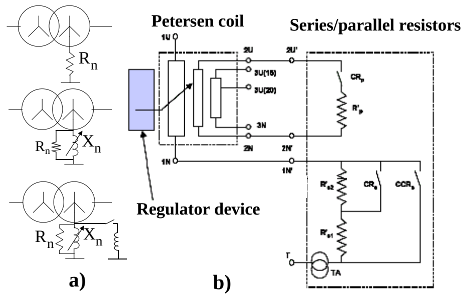


Figure 4: possible connection of grounding impedances to MV neutral winding of HV/MV transformers and equivalent circuit of the automatic tunable impedance

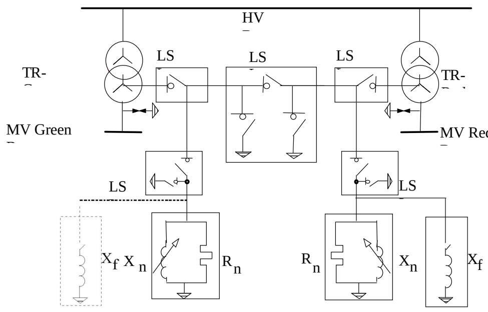


Figure 5: automatic tunable coil with integral resistance plus external off-load tunable coil (adopted for I_{CF}=300÷480 A)

Furtermore in case of loss of the neutral resistor R_n, the control system automatically disconnects the Petersen coil, and the MV network come back to the ungrounded system.

The Udine Rotonda 20 kV ENEL network studied

To strengthen the above results, a study was carried out with ATP program simulating ENEL Distribuzione PS Udine Rotonda 20kV network (Figure 6).
The simulated 20 kV ENEL network has an overall line length of 197 km, with a capacitive 1-Φ-to-Gr fault current of the network of 308 A.
The 1-Φ-to-Gr bolted faults are simulated, both at the end of the Basiliano 20.3 km long mixed overhead-cable feeder, and at PS. Following MV neutral connections were simulated:

- ungrounded;
- grounded by a Petersen coil paralleled with a resistance (Figure 7.a- ENEL practice);
- grounded only by means of a Petersen coil (Figure 7.b, active current due only to internal losses of neutral impedance and earthing transformer);
- grounded with a resistance (385 Ω; 38.49 11.55 Ω).

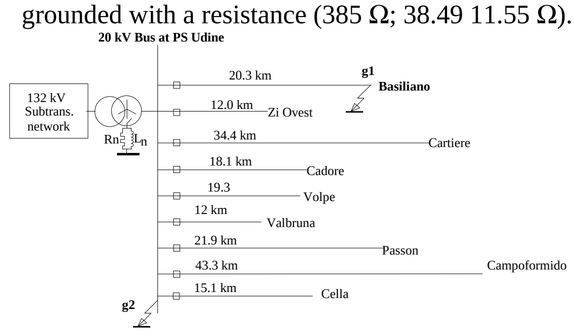


Fig. 6- The studied Udine Rotonda ENEL-Distribuzione 20kV-50 Hz network studied

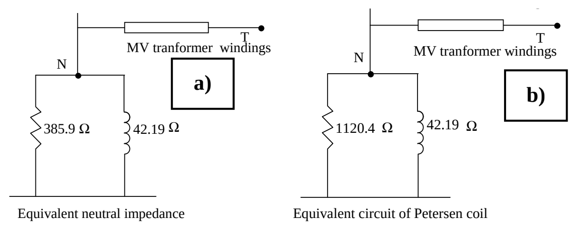


Fig. 7- Equivalent circuits of 132/20 transformer neutral ground connection at Udine PS

Main voltages and currents calculated by ATP are reported in Table I for all neutral grounding connections simulated.
Analyzing results of Table I, the following significant remarks can be made:

- for ungrounded neutral, 1-Φ-to-Gr fault occurring at the end of the mixed overhead-cable line Basiliano causes significant healthy phase TOVs (2.3 p.u.). TOVs remain high (2.25 p.u.) even if the neutral is grounded only by 388.7 Ω resistor. Lower ohmic value grounding resistors reduce TOVs below 2 p.u. (1.94 p.u. and 1.54 p.u for R_n=38.5Ω and 11.5 Ω, respectively);
- the Petersen coil, stand alone or in parallel with a resistor, is a very effective mean to reduce TOVs (maximum of 1.8 p.u.);
- as theoretically predicted, ground faults near the PS cause TOVs not greater than 1.8. p.u., whatever neutral grounding connection is adopted;
- for ungrounded neutral, 1-Φ-to-Gr fault at the end of Basiliano line causes a fault current of 434 A, i.e. 1.38 times the network capacitive fault current. The Petersen coil drastically limits the fault current also in case of faults at the end of long line;
- considering, finally, low resistance neutral grounding (11.55 Ω), only if the 1-Φ-to-Gr fault occurs near to the PS, the current flowing in the grounding resistor is nearly the rated current value; for faults faraway the PS, both the fault current and the current in the grounding resistors are drastically reduced.

Table I: main results for a 1-Φ-to-Gr bolted fault located at the end of a 20.3 km mixed-overhead-cable line Basiliano and in the PS [4]

Neutral grounding	Fault location	E_{oSS} [p.u.]	E_{maxSS} [p.u]	E_{oPS} [p.u.]	E_{maxPS} [p.u]	$I_{1\Phi\text{-to-Gr}}$ [A]	I_{Xn} [A]	I_{Rp} [A]
Ungrounded	SS Bas.no	1.15	2.06	1.42	2.30	434	-	-
Rn//Xn 388.7/43.3 Ω	SS Basiliano	1.04	1.80	0.96	1.80	34	254	26.9
Xp 43.3Ω	SS Basiliano	1-04	1.80	0.99	1.80	18	258	-
Rn=385 Ω	SS Basiliano	1.14	2.04	1.36	2.25	349	-	40.3
Rn=38.5 Ω	SS Basiliano	0.97	1.85	0.95	1.94	372	-	285
Rn=11.55 Ω	SS Basiliano	0.81	1.61	0.51	1.54	516	-	509
Ungrounded	*PS*	-	-	*1.05*	*1.81*	*314*	-	-
Rn//Xn 388.7/43.3 Ω	*PS*	-	-	*0.98*	*1.81*	*35*	*264*	*27.3*
Xp 43.3Ω	*PS*	-	-	*0.98*	*1.81*	*18*	*256*	-
Rn=385.6 Ω	*PS*	-	-	*1.06*	*1.83*	*276*	-	*31.9*
Rn=38.5 Ω	*PS*	-	-	*1.06*	*1.86*	*420*	-	*318*
Rn=11.5 Ω	*PS*	-	-	*1.06*	*1.88*	*1094*	-	*1055*

Preliminary results of field test performed on the 20 kV network Udine Rotonda

In order to verify on field the theorically predicted overvoltages, experimental tests on the actual Udine Rotonda 20 kV ENEL network were performed applying a bolted 1-Φ-to-Gr fault at Basiliano SS and at PS (Figure 6) and recording the voltages and current at PS.

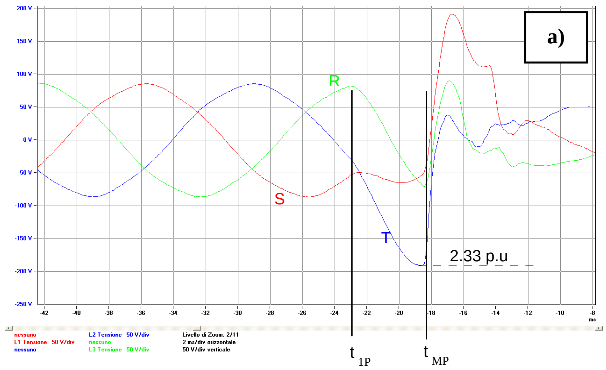
Preliminary analyses of the recordings show a good agreement between the theoretical predicted values and measured overvoltages.

Network with ungrounded Neutral

In Figure 8 the measured and ATP calcutated voltages at PS for a 1-Φ-to-Gr fault at Basiliano SS are reported, in case of ungrounded MV neutral,

The maximum PS busbars TOV (2.33 p.u.) is present on phase T after about 4÷5 ms the fault inception. At time t_{Mp} the overvoltages on the healthy phases caused further ground faults on Cartiere 20 kV line, which evolved in a permanent three-phase as can be seen from Figure 8.a behind the time t_{Mp}.

Comparing Figure 8.a with Figure 8.b it can be noticed that the shape and the calculated values (max. value on T phase is 2.30 p.u.) of PS overvoltages are practically the same until the inception of the multi-phase fault in the Cartiere line.



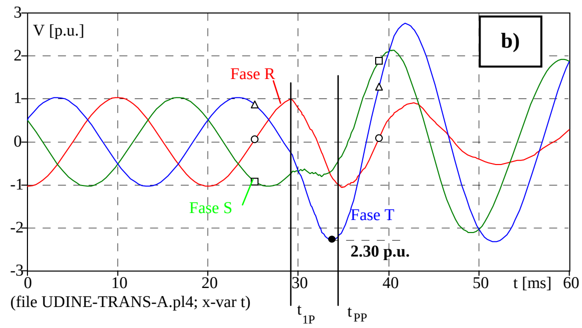


Figure 8: voltages at PS versus time following the 1-Φ-to-Gr bolted fault at Basiliano SS: a) Measured voltages; b) ATP calculated

Network with neutral grounded by a compensating impedance X_n//R_n

Figure 9 refers to the 1-Φ-to-Gr fault at Basiliano SS in case of neutral grounded by compensation impedance.

Also in this case, the measured value of the healthy phases at PS (Fig. 9.a) are in very good agreement with ATP results: TOV recorded is 1.77 p.u., the calculated one is 1.81 p.u. (1.p.u.=20/√3 kV).

The analysis of the other experimental tests performed (1-Φ-to-Gr fault at Basiliano SS and at PS with different neutral grounding), not reported here for brevity, show a very good agreement with ATP simulations, confirming the soundness of the above given treatment.

4 PS MV busbar voltage section prior to fault 1.05 p.u. (1.1 p.u=20/√3 kV); I_{CF}=314 A

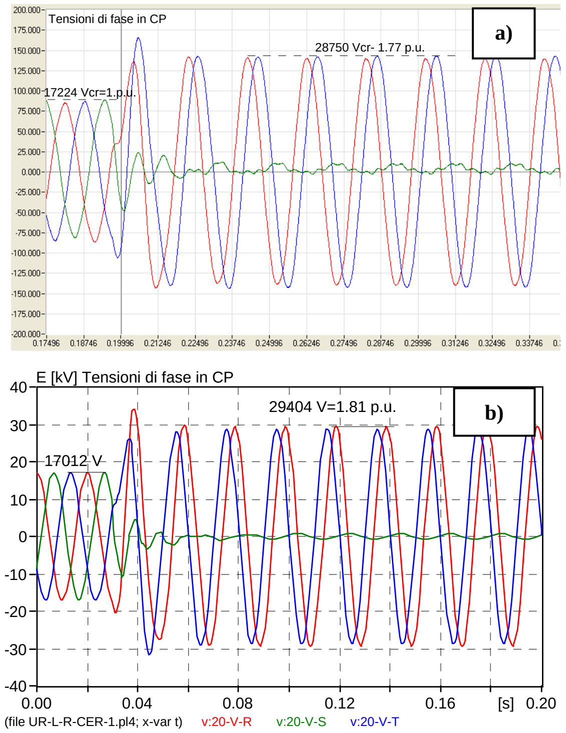


Figure 9 – Compensated neutral -Voltages at PS versus time following the 1-Φ-to-Gr bolted fault at Basiliano SS: a) Measured voltages; b) ATP simulation

CONCLUSIONS

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

The main following conclusions can be outlined:

- for networks with ungrounded neutral, the 1-Φ-to-Gr faults at the receiving end of long overhead lines can cause abnormal healthy phase overvoltages (2.2–3 p.u.), especially at PS busbars;
- experimental field tests performed on the real 20 kV-Udine Rotonda network of ENEL Distribuzione fully confirm theoretically predicted TOVs: in case of ungrounded neutral measured TOVs have been 2.33 p.u., 2.30 p.u. calculated by ATP;
- the paper shows that, with the ENEL neutral practice i.e using a compensation impedance (Rn||Xn) the TOVs are drastically suppressed. The same reduction can be obtained with only Petersen coil;
- grounding the neutral by a simple resistor (388.5 Ω - I_n=30 A at 20/√3 kV) does not suppress the TOVs (for the 20 kV Udine Rotonda ATP calculated, TOVs remain high, i.e. 2.25 p.u.). TOV reduction below 1.9 p.u. requires grounding resistances significantly lower, say 38.5 Ω -300 A at 20/√3 kV.

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