PERFORMANCE OF THE COMMON GROUNDING SYSTEM DURING GROUND FAULTS

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SUMMARY

The paper deals with the performance during ground faults of MV/LV substation grounding systems belonging to a “Common Grounding System” as per CENELEC HD 637 S1-1999 E. A parametric analysis is performed, by means of ATP-EMTP, on a typical 150/20/0.4 kV distribution system, considering the MV neutral ungrounded or resonant-grounded. Results obtained highlight the benefits brought by the Common Grounding System but also fault conditions, such as double-earth-fault on MV line(s) or 1-Phase-to-Ground fault HV side in the HV/MV substation, which can still generate significant touch and step voltages that should not be disregarded in the system grounding design.

INTRODUCTION

In continental Europe, MV public distribution networks are generally operated in radial configuration, while neutral grounding practices differ widely: isolated or resonant grounded in Italy, resistance grounded or resonant grounded in Spain and France, resonant grounded in Germany and, in general, in Northern Europe, that is, everything except solid grounding. In these networks the connection of the metallic sheaths/screens of the underground cables to the grounding system of the HV/MV and MV/LV distribution substations is a widespread practice among Distributors, and allows to reduce the grounding resistance together with the touch and step voltage during ground faults.

Past Italian Standards foresaw the design of the grounding system disregarding the connections of the cable metallic sheaths/screens to grounding systems. Current European harmonization documents [1], received as national Standards [2], have at last introduced the possibility of considering in the grounding system design the above connections, by fostering the so-called “Common Grounding System” (CGS) concept. The CGS consists in the interconnection of the grounding systems of all MV/LV substations to that of the HV/MV substation supplying the MV network, by means of the MV cables’ metallic sheaths/screens and/or of dedicated ground conductors buried along the MV cables. The grounding interconnection reduces the grounding resistance and creates, in parallel with the earth path, a metallic ground–fault current path which is able to drain away most of the fault current.

This metallic-return current does not flow in the grounding system at the fault point (Fig. 1): due to the reduced touch and step voltages the Standard [2] allows simplified design criteria for the grounding systems participating in a CGS. However, the end-of-line MV/LV substation in a radial system might actually be disconnected from the CGS, and therefore in case of a fault to ground in this substation the total fault current would to be dispersed only by the local grounding system.

While technically justified, the unconditional acceptance of the Standard provisions requires also the investigation on possible, even if less likely, operation/fault conditions [3], [4]. For instance, in case of two simultaneous 1-Phase-to-Ground-Faults (1-Φ-to-Gr) at different locations, i.e. “Cross-Country Fault” (CCF), a significant ground current has to be drained by the grounding system of the faulted substations. (Fig.2).

Finally, in case of 1-Φ-to-Gr fault occurring at HV side in the HV/MV primary substation the earth voltage (Ue) at MV/LV distribution stations may attain high value due to large fault

Fig.1 - The return path of I in case of cable sheaths connected to the MV/LV and HV/MV substations’ grounding systems: a) Three-phase equivalent circuit; b) Connection of sequence circuits.

Fig.2 - Return path of I in case of cable sheaths/screens connected to the MV/LV substations’ grounding systems; MV network with ungrounded neutral.
current, also in case of existence of the CGS (Fig. 3).

In next paragraphs a parametric analysis is reported when a 1-Φ-to-Gr fault occurs in HV/LV or MV/LV substations, for the most usual MV neutral operations adopted in Europe, and in case of a CCF occurring in one of the MV lines originating from the primary distribution substation.

Fig. 3 - 1-Φ-to-Gr fault occurring at HV side in the HV/MV primary substation possibly generating high Ue of the Common Ground System.

THE STUDIED 150/20/0.4 KV DISTRIBUTION SYSTEM

For the performed parametric analysis the 400/150/20/0.4 kV distribution system of Fig. 4 has been simulated by ATP. This network structure, referred to as “island” configuration, is one of the usually adopted in Italy: the 150 kV subtransmission network is made up of some 150 kV lines originating from a 400/150 kV station and terminating in another 400/150 kV station. Along the 150 kV lines are located the primary 150/20 kV substations, from which the radially operated 20 kV lines originate. In case the MV lines terminate in another HV/MV substation, they are sectionalized for radial operation.

The main system component characteristics are reported in Tables I and II. The 20 kV distribution network originating from the 150/20 kV primary substation is made of 8 underground cable lines 2 km or 4 km or 6 km long, with 10 secondary substations (20/0.4 kV) along each cable, spaced 200 m or 400 m or 600 m, respectively.

The grounding resistances of the 150/20 kV substations, R_Eps, and of the 20/0.4 kV substations, R_Ess, have been assumed equal to: R_Eps=1-2 Ω, R_Ess=5-10 Ω.

The following connection to ground of the 20 kV network neutral has been considered:

- a) Isolated from ground;
- b) Connected to ground by a parallel resonant inductive reactance of 166.4 Ω, 83.2 Ω and 55.5 Ω for the assumed total length of the 20 kV lines of 16 km, 32 km and 48 km, respectively. Inductance and resistance values have been chosen to compensate 105% of the capacitive fault current, with a resistive fault current in the 20-40 A range (current distribution practice in Italy)

SIMULATION RESULTS

1-Φ-to-Gr Fault in a MV Line

With ungrounded neutral or resonant grounding, the overall 1-Φ-to-Gr fault current in a MV/LV substation is practically unaffected by the grounding resistance of the faulted substation (Tab. III).

With ungrounded neutral and R_Ess= 5 Ω, when the CGS is in normal condition, i.e. the HV/MV substation grounding and all grounding systems of the MV/LV substations are
interconnected, the current drained in the local ground, \( I_E \), is not greater than 12% of \( I_{k1} \); the attendant \( U_E \) is always less than 120 V and usually under 100 V; the most severe fault occurs in the line-end MV/LV substation of each feeder. With \( R_{ess} = 10 \Omega \), the current drained in the local grounding system, \( I_E \), is less than 9% of \( I_{k1} \) and max. \( U_E \) is 170 V.

For the admittedly conservative example of a purely radial MV feeder, interruption of the cable screens, i.e. separation of several MV/LV substation grounds from the CGS, causes a severe increase of \( U_E \). This is due to the increase of the effective grounding resistance “seen” at the fault point: the worst case is the interruption of cable screens at the line-end MV/LV substation, so that the equivalent ground resistance coincides with the substation ground resistance \( R_{ess} \) (100% of MV/LV substation, so that the equivalent ground resistance is \( 0.1 \) of \( R_{ess} \)).

\[
U_E = R_{ess} \times I_{k1}; \quad \text{depending on the network extension.}
\]

\( U_E \) values are in the range 320-1000 V for \( R_{ess} = 5 \Omega \); with \( R_{ess} = 10 \Omega \), \( U_E \) is 640-1980 V. Interruption of the cable screens at the HV/MV substation, i.e. disconnection from the substation ground mat, is a less severe contingency, but \( U_E \) is found in the 46-233 V and 73-340 V range for \( R_{ess} = 5 \Omega \) and \( R_{ess} = 10 \Omega \), respectively.

Resonant grounding considerably improves the system performance, because 1-Φ-To-Gr fault current is limited to about 30 A for the largest simulated network, as shown by Table III. With CGS in normal condition and \( R_{ess} = 5 \Omega \), \( I_E \) is not greater than 14% of \( I_{k1} \); \( U_E \) reaches a maximum of 22 V. For \( R_{ess} = 10 \Omega \), values are 11% and 32 V. In the milder instance of CGS separation, with the screens not connected to the HV/MV substation ground mat, \( U_E \) is still under 100 V (48km network, \( R_{ess}=10\Omega \), \( U_E=98 \) V, see Tab. IVb).

Even with resonant grounding, however, the isolated end-of-line substation ground yields \( U_E \) values in the range 213-303 V for \( R_{ess}=10 \Omega \) (107-153 V for \( R_{ess}=5 \Omega \)). The main results of the parametric analysis, for \( R_{ess}=10\Omega \), are reported in Table IV.

### Cross-country fault in a MV line

Cross-Country Faults have been simulated only for resonant-grounded networks: results with different neutral grounding are not dissimilar, since the fault is basically two-phase. Furthermore the grounding resistance of the faulted substations does not practically reduce the fault current, which flows mainly in the cables screens. High values of fault current \( I_{kEE} \) and \( U_E \) are originated by a CCF, even if the effectiveness of CGS in diverting a large share of \( I_{kEE} \) from the grounding system of the faulted MV/LV substations drastically reduces \( U_E \) with respect to the case of ungrounded screens.

Table V reports the values of \( I_{kEE} \) and \( U_E \) in case of a CCF involving MV/LV substations of the same feeder, with CGS in normal condition and with grounding resistance of the MV/LV substation \( R_{ess}=10 \Omega \). The maximum \( I_{kEE} \) occurs when the CCF takes place in the two first MV/LV substations of the faulted line. In this case \( I_{kEE} \) is in the range of 7.3-7.7 kA and \( U_E \) is between 444 and 1015 V.

On the contrary the highest \( U_E \) occurs when the CCF involves the first and the last MV/LV substation of the faulted feeder. In this case \( U_E \) is between 2350 V and 4070 V. Moreover, due to the fault current magnitude and the interconnection of MV grounding systems, \( U_E \) attains significant values also in other unfaulleted substations: e.g., with \( R_{ess}=10 \Omega \), a CCF involving the first and the last MV/LV substation, raises \( U_E \) at the substation before the last one up to 3270 V.

### Table IVa: 20 kV network with ungrounded neutral – \( U_E \) and fault current for a 1-Φ-to-Gr fault in the MV network

<table>
<thead>
<tr>
<th>Subst.</th>
<th>Faulted Screens connection</th>
<th>( I_E ) [A]</th>
<th>( U_E ) [V]</th>
<th>Faulted Screens connection</th>
<th>( I_E ) [A]</th>
<th>( U_E ) [V]</th>
<th>Faulted Screens connection</th>
<th>( I_E ) [A]</th>
<th>( U_E ) [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>10</td>
<td>63.7</td>
<td>4.7</td>
<td>10</td>
<td>129</td>
<td>7.1</td>
<td>10</td>
<td>196</td>
<td>16.9</td>
</tr>
<tr>
<td>01</td>
<td>63.8</td>
<td>11.5</td>
<td>73.4</td>
<td>01</td>
<td>129.3</td>
<td>14.5</td>
<td>01</td>
<td>197</td>
<td>17.3</td>
</tr>
<tr>
<td>06</td>
<td>64</td>
<td>20.1</td>
<td>128.3</td>
<td>06</td>
<td>131</td>
<td>21.2</td>
<td>06</td>
<td>201</td>
<td>22.5</td>
</tr>
<tr>
<td>10</td>
<td>64</td>
<td>100</td>
<td>640</td>
<td>10</td>
<td>130</td>
<td>100</td>
<td>10</td>
<td>198</td>
<td>100</td>
</tr>
</tbody>
</table>

### Table IVb: 20 kV network with resonant neutral grounding – \( U_E \) and fault current for a 1-Φ-to-Gr fault in the MV network

<table>
<thead>
<tr>
<th>Subst.</th>
<th>Faulted Screens connection</th>
<th>( I_E ) [A]</th>
<th>( U_E ) [V]</th>
<th>Faulted Screens connection</th>
<th>( I_E ) [A]</th>
<th>( U_E ) [V]</th>
<th>Faulted Screens connection</th>
<th>( I_E ) [A]</th>
<th>( U_E ) [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>10</td>
<td>21.7</td>
<td>5.0</td>
<td>10</td>
<td>25</td>
<td>8.1</td>
<td>10</td>
<td>31</td>
<td>10.4</td>
</tr>
<tr>
<td>01</td>
<td>22.3</td>
<td>14.7.5</td>
<td>33</td>
<td>01</td>
<td>27</td>
<td>21.6</td>
<td>01</td>
<td>35</td>
<td>27.9</td>
</tr>
<tr>
<td>06</td>
<td>21.6</td>
<td>22.1</td>
<td>48</td>
<td>06</td>
<td>25</td>
<td>25.5</td>
<td>06</td>
<td>31</td>
<td>28.8</td>
</tr>
<tr>
<td>10</td>
<td>21.3</td>
<td>100</td>
<td>213</td>
<td>10</td>
<td>24.5</td>
<td>100</td>
<td>10</td>
<td>30.3</td>
<td>100</td>
</tr>
</tbody>
</table>
Screen interruptions are liable to cause exceptionally high \( U_E \) values when they involve a cable section upstream one or both the faulted substations. In the limit case of screens interrupted at last MV/LV substation, with the CCF involving the first and the last MV/LV substations, \( U_E \) is very high, in the range 11.4-17.9 kV, even though the CCF current is lower (1.14 kA - 1.79 kA) than in case of CGS in normal conditions.

On the other hand, it must be pointed out that such dangerous conditions can persist only for a short time, as the line tripping time for multiphase faults (if the faults are on the same line), or first-line tripping time for double 1-Φ-to-Gr fault on different lines, is about 100 ms.

### 1-Φ-to-Gr Fault in the HV supply network

The implementation of a CGS creates a metallic connection between the grounding systems of the HV/MV substation and of all MV/LV substations. This implies that in case of unbalanced ground fault in HV supply system, notably in the HV/MV substation, there is a voltage rise also in the MV/LV substation grounds, due to the sharing of fault current. These voltages are generally significant as the HV ground fault currents are large, due to neutral solidly grounded in the HV subtransmission network. Shield wires of HV overhead lines and screens/armours of HV cables have beneficial effects, reducing the fault current actually drained by the HV substation grounding mat [5]. The voltage \( U_E \) occurring at nearby MV/LV substations can nevertheless be of concern. In addition, the problem may be exacerbated if the LV neutral conductor is connected to the MV/LV substation ground system. In this case, \( U_E \) would be directly transferred to LV customers.

The ATP-EMTP parametric analysis of the effects of HV-side 1-Φ-to-Gr fault in the HV/MV primary substation has been carried out for the system of Fig.4 considering the following values of the ground resistances of the primary and secondary substations: \( R_{EPS}=0.5-1-2 \ \Omega \) and \( R_{ESS}=5-10 \ \Omega \). The tower grounding systems, where shield wires of the 150 kV lines are connected, have been simulated by a 20 \( \Omega \) ground resistance. The CGS has been considered both in normal condition and in the already considered contingency conditions. For the studied system the value of the 1-Φ-to-Gr fault current at HV side of the HV/MV primary substation, \( I_{EHV} \), is 5.1 kA.

Table VI reports \( U_E \) at the primary and at the nearest secondary substation (MV/LV subst. 1 in Fig.4), for different values of ground resistance and extension of the MV network supplied from the faulted primary substation.

### Table VI - \( U_E \) at primary and at secondary substation following a 1-Φ-to-Gr fault at HV side of the HV/MV primary substation with CCS in normal condition

<table>
<thead>
<tr>
<th>MV network extension</th>
<th>16 km</th>
<th>32 km</th>
<th>48 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{EPS} \ [\Omega] )</td>
<td>( R_{ESS} \ [\Omega] )</td>
<td>( U_{EPS}/U_{ESS} \ [V] )</td>
<td>( U_{EPS}/U_{ESS} \ [V] )</td>
</tr>
<tr>
<td>0.5</td>
<td>5</td>
<td>447 / 384</td>
<td>597 / 479</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>488 / 420</td>
<td>672 / 539</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>681 / 624</td>
<td>856 / 738</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>512 / 440</td>
<td>717 / 575</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>731 / 669</td>
<td>934 / 805</td>
</tr>
</tbody>
</table>

Results, shown in Tab. VI, point out the following main remarks:

- The CGS efficiently cuts down the HV/MV primary substation ground grid \( U_E \) because the interconnected grounding systems of all MV/LV substations reduce the effective ground resistance to 0.05±0.33 p.u. of the HV/MV grounding system resistance;
- For more usual values of \( R_{EPS}=1 \ \Omega \) and \( R_{ESS}=10 \ \Omega \), the primary substation \( U_E \) is reduced at values between 13.5% and 20% of the \( U_{EPS} \) occurring if fault current is dispersed only by the primary substation ground grid (\( U_E = R_{EPS} I_{EHV},=5.1x1=5100 \) V);
- Higher values of \( R_{EPS} \) and \( R_{ESS} \) yield, as expected, higher \( U_E \);
- Lower values of \( U_E \) occur with an higher number of MV/LV substations and with a decreasing distance between them;
- High potentials, in the range of 385V-922 V (1.7-4.0 p.u., 1.p.u.=230 V) are transferred to the MV/LV substation nearest to the primary substation, thereby increasing the phase-to-ground voltage at LV to dangerous values for the LV users and equipment.

To avoid the above high transferred potentials the following measures can be adopted:

a) The screens/sheaths of all MV cable lines originating from primary substation can be connected to a dedicated grounding system, separated from the primary substation ground mat;

b) The connection to ground of the LV neutral can be done in a grounding system separate from the MV/LV substation ground, in such a way that the MV/LV substation \( U_E \) is not or only partially transferred by mutual coupling to the LV network. This measure is however foreseen by the current Italian Standard [2].

### CONCLUSIONS

The paper dealt with the Common Grounding System (CGS) introduced by the CENELEC HD 637 S1-1999 E. An ATP-EMTP parametric analysis has been performed on a typical...
150/20/0.4 kV Italian distribution system with MV network in radial configuration, taking into account different values of MV network extension, ground resistance of HV/MV and MV/LV substations, MV network neutral status, in order to quantify the CGS performance during ground faults in the HV and MV networks. The results obtained show that the CGS drastically reduces $U_E$ values (and thus, step and touch voltages) during 1-$\Phi$-to-Gr faults and Cross-Country Faults. Nevertheless, analysis of abnormal CGS condition, i.e. disconnection of cable screens/sheaths from the grounding system of MV/LV substations, may cause significantly high values of $U_E$, that should be taken into account in the MV/LV grounding design.

In case of HV side 1-$\Phi$-to-Gr fault in the HV/MV primary substation the study has quantified the high transferred potential to the MV/LV substation in the presence of a CGS.

REFERENCES


