A study of the behaviour of earth electrodes connected together in resonant earthed neutral systems

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Abstract

Inside urban areas the earth electrodes of the MV/lv substations are often electrically connected together so as to form a single extended earthing system. The advantages of the realization of an extended earthing system are the reduction of the current that each substation earth electrode injects in the soil during the fault and a better uniformity of the voltages to earth inside the urban area.

In previous works, models for the study of extended earthing systems have been proposed. These models were valid for the case of single-line-to earth fault in isolated neutral MV networks. In this paper, the extended earthing system is analyzed in the case of a resonant earthed neutral MV network. The mathematical model used for the analysis and an application example are shown and a comparison with the case of isolated neutral system is done.

Keywords: resonant earthed neutral system, interconnected earthing systems, extended earthing system, MV/lv substations.

1 Introduction

The design of the earthing system of the MV/lv substations is often a complicated and onerous task, considering the high values of the fault currents usually present. A measure to reduce the design currents of the earthing systems consists in connecting together all the earth electrodes, using, for example, the metal sheath of the cable lines of the MV network.

The presence of numerous interconnected earthing systems creates, however, a number of safety problems, due to the transfer of voltages, which need to be analysed.
The works [1–3] face these problems in a systematic manner with reference to isolated neutral MV networks and describe a general analysis methodology.

However, in recent years, the European Distribution Societies have changed the state of the neutral point in their networks, passing from an exercise with isolated neutral to an exercise with neutral connected to earth by a resonant impedance.

The resonant impedance causes, during the fault, the circulation of an inductive current in the network that adds itself to the fault current, capacitive by own nature, and reduces its value. Often the compensation of the capacitive fault current is not total but it’s in the range 85%–95%. Therefore, in resonant earthed neutral systems single-line-to-earth currents assume lower values with respect to the isolated neutral systems but, on the contrary, the intervention times for earth leakage of the protection devices are higher. (Intervention time for earth leakage: Isolated neutral systems \( t_F = 0.3–1\)s; Resonant earthed neutral systems \( t_F = 10\)s.)

On the basis of these considerations an analysis of the safety conditions in these networks becomes necessary, also considering the different distribution of the earth fault current between the interconnected earthing systems, because of the presence of the inductive current due to the resonant impedance.

In this paper the methodology presented in [1–3] is applied to a resonant earthed neutral MV network, to investigate on how the safety conditions change.

2 Model for the analysis of the extended earthing system

Figure 1 shows a HV/MV station supplying \( M \) MV sheathed tri-core cable lines. Every line feeds \( N \) MV/lv substations. The sheaths are connected to the earthing systems of all the substations of the related lines. A single-line-to-earth fault is assumed to occur inside the \( h^{th} \) substation of one of the MV lines.

![Figure 1: Schematic representation of the MV network.](image-url)
In this situation a part of the fault current $I^F$ is injected in the soil by the earthing system of the faulted substation and a part is drained by the metal sheath of the faulted line.

The current through the sheath partly goes back to the HV/MV station through the capacitance between the sheath and the unfaulted phase conductors, and partly is injected in the soil by the earthing systems of the unfaulted substations.

The study of this system is done using a matrix approach based on the subdivision of the network in partial models.

In these models all the phenomena of capacitive and inductive coupling between the conductors of the system are taken into account. The influence of the earth is computed applying the Carson’s theory.

Moreover, the different situations that can take place in the practice, with reference to the interconnection of the earthing systems of the MV/lv substations and of the HV/MV station can be studied. In MV networks, indeed, it’s possible:

A to connect together the earthing systems of all the substations of the network and of the HV/MV station;

B to connect together the earthing systems of all the substations of the network but not the earthing system of the HV/MV station;

C to connect together only the earthing systems of the substations supplied by the same MV line, but to keep them separated by the earthing systems of the station and of the substations of the other lines.

Figures 2 and 3 show the circuital models of the generic $i^{th}$ section of the faulted line, located, respectively, above and below the substation in which the fault occurs.

With $I^F$, $I^b_i$, $I^c_i$, $I^s_i$ and $I^g_i$ are indicated, respectively, the fault current and the currents, flowing in the phase conductors $b$ and $c$, in the metal sheath $s$ and in the earth $g$. The subscripts $i-1$ and $i$ indicate, respectively, the input and the output voltages and currents of the two circuits.

![Figure 2: Equivalent circuit of a generic section of the faulted line, above the fault location.](image-url)
z and \( z' \) are the own impedances of the of the phase conductors and of the sheath, respectively.

\( z^e \) is the impedance of the earth.

The current controlled voltage sources in figures 2 and 3 represent the voltages induced in each conductor by the currents flowing in the other parallel conductors. Their expressions are, together with the expression of \( z \), \( z' \) and \( z^e \) in Appendix 1.

\( R_E \) is the earth resistance of the earthing system of a generic substation, supposed equal for all the substations.

\( c \) is the distributed shunt capacitance between an unfaulted conductors and the sheath.

\( \ell_i \) is the length of the \( i^{th} \) section.

The input/output relations of the circuits in figures 2 and 3 are, respectively:

\[
\begin{bmatrix}
\overline{V}_{i-1}^a \\
\overline{V}_{i-1}^b \\
\overline{V}_{i-1}^c \\
\overline{V}_{i-1}^g \\
\end{bmatrix} = 
\begin{bmatrix}
\alpha_i \\
\beta_i \\
\gamma_i \\
\delta_i \\
\end{bmatrix}
\begin{bmatrix}
I_{i-1}^a \\
I_{i-1}^b \\
I_{i-1}^c \\
I_{i-1}^g \\
\end{bmatrix} + 
\begin{bmatrix}
\alpha_i \\
\beta_i \\
\gamma_i \\
\delta_i \\
\end{bmatrix}
\begin{bmatrix}
I_i^a \\
I_i^b \\
I_i^c \\
I_i^g \\
\end{bmatrix}
\]

The matrices appearing in eqn. (1) can be easily obtained by applying Kirchhoff’s laws to the circuits in figures 2 and 3.

The model of the generic section of an unfaulted line, represented in figure 4, is similar to the one shown in figure 2 and a relation analogous to eqn. (1) can be found for it.

The circuital representation of the HV/MV station is shown in figure 5, in the case of only two lines leaving the station.

Figure 3: Equivalent circuit of a generic section of the faulted line, below the fault location.
In figure 5:
- $Z_L$ is the resonant impedance, connected through the neutral of the transformer and the earth;
- $R_{SS}$ is the earth resistance of the station;
- $E_a$, $E_b$ and $E_c$ are three voltage sources whose value is equal to the phase to neutral voltage of the MV network.

In order to obtain a circuitial model valid for every state of the connection between the metal sheaths of the MV lines and the earthing system of the station, a virtual switch in every metal sheath and above the point where all the sheaths converge is introduced. If a sheath is not connected to the earthing system of the HV/MV station the related switch is open, on the contrary it’s closed. When all the sheaths are not connected to the earthing system of the station the switch $S_R$ is open.
For the circuital model in figure 5 the following equation can be written (see Appendix 2):

\[
\begin{bmatrix}
\bar{E}_b - \bar{E}_a \\
\bar{E}_c - \bar{E}_b \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
= \begin{bmatrix}
\sigma_f \cdot \bar{I}_0, f \\
0 \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
= \begin{bmatrix}
\bar{V}_{u,0} \\
\bar{V}_{u,0} \\
\bar{V}_{u,0} \\
\bar{V}_{u,0} \\
\bar{V}_{u,0} \\
\bar{V}_{u,0} \\
\bar{V}_{u,0}
\end{bmatrix}
(2)
\]

Analogues equations can be written in the case of more than two MV lines leaving the HV/MV station.

Combining the equations that describe the behaviour of the various part of the network, a system of linear equations is written that gives the currents and the voltages in all the sections of the faulted line and of the unfaulted ones, imposing the following boundary conditions:

\[
\begin{align*}
\bar{I}_N,u &= \bar{I}_C,u = \bar{I}_N,f = \bar{I}_C,f = 0; \\
\bar{I}_N,u + \bar{I}_N,f &= 0; \\
\bar{I}_N,f + \bar{I}_N, f &= 0;
\end{align*}
\]

\[
\bar{V}_{N,u} = 2 \cdot R_E \cdot \bar{I}_{N,u}; \\
\bar{V}_{N,f} = 2 \cdot R_E \cdot \bar{I}_{N,f}
\]

(3)

3 Application example

The model has been applied to the study of the MV network whose characteristics are listed in table 1.

The network is composed by 5 identical tri-core cable lines. Every line is 6 km long, has only one metal sheath and supplies 20 substations. The distance between the substations is 300 m.

With reference to the interconnection between the earthing systems of the substations and the earthing system of the station, the three situations A, B and C listed in the previous paragraph are considered.

The analysis is done by a comparison, for each case (A, B and C), of the behaviour of the resonant earthed neutral network with the behaviour of the same network with isolated neutral. This comparison is done studying the trend of the voltage to earth \(U^{gs}\) of all the earthing systems.

This investigation allows one to obtain useful information having general validity.

In figure 6 the results of the simulation for the resonant earthed neutral network are shown.
Table 1: Characteristics of the network.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faulted substation</td>
<td>10</td>
</tr>
<tr>
<td>Earth bulk resistivity [Ω m]</td>
<td>100</td>
</tr>
<tr>
<td>Electric resistance per unit of length of the phase conductor [Ω/km]</td>
<td>0.387</td>
</tr>
<tr>
<td>Diameter of the phase conductor [mm]</td>
<td>8.1</td>
</tr>
<tr>
<td>Distance between the phase conductors [mm]</td>
<td>8.3</td>
</tr>
<tr>
<td>Mean distance between the phase conductors and the metal sheath [mm]</td>
<td>11.5</td>
</tr>
<tr>
<td>Electric resistance per unit of length of the metal sheath [Ω/km]</td>
<td>0.76</td>
</tr>
<tr>
<td>Mean diameter of the sheath [mm]</td>
<td>23</td>
</tr>
<tr>
<td>Capacitance per unit of length between a phase conductor and the metal sheath [µF/km]</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Figure 6: Trend of the voltage to earth for a) RE=5Ω; b) RE=20Ω in a resonant earthed neutral system.

Figure 7 shows instead the results of the simulation done for the same network with isolated neutral.
Analysing the trend of the voltages to earth shown in fig. 6, the following considerations can be done:

a. $U_{sg}$ is lower than 10V for $R_E=5\Omega$ and lower than 25V for $R_E=20\Omega$.

b. Starting from the faulted substation, $U_{sg}$ at first decreases and then rises again.

c. The maximum of $U_{sg}$ can be, in some cases at the fault location, in some other cases inside an unfaulted substation.

d. The highest values of $U_{sg}$ are found in the case B.

Instead, analysing the trend of the voltages to earth in fig. 7, for the isolated neutral network:

- $U_{sg}$ is lower than 50V for $R_E=5\Omega$ and lower than 120V for $R_E=20\Omega$.
- The trend of $U_{sg}$ is more regular than in the case of resonant earthed neutral network, with a maximum usually at the faulted substation (cases A and B), except in the case C where two maximum, having values very closer, can be.
- The highest values of $U_E$ are found in the case C. In fact, in this case, because of the absence of the metallic connection between the metal sheaths of the different lines, the whole fault current is dispersed by the earthing systems of the substations of the faulted line.
- The trends of $U_{sg}$ in the cases A and B are very similar.

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**Figure 7**: Trend of the voltage to earth for a) $R_E=5\Omega$; b) $R_E=20\Omega$ in an isolated neutral system.
4 Conclusion

For the design of the earthing systems of the MV/lv substations it’s possible to refer to the safety conditions imposed in standards IEC-479-1 and CENELEC HD 637 S1.

According to the Standards, the earth resistance of a MV/lv substation must be able to verify the condition $U_E = U_{sg} \leq 1.5 U_{Tp}$, being $U_{Tp}$ the permissible touch voltage depending on the intervention time of the protection device above the fault location.

In resonant earthed neutral networks in order to assure a better continuity of supply, the intervention time is higher than in isolated neutral networks (10 s against 0.3–1 s). This implies that, in the first case, the values of $U_{Tp}$ which refer to are about the 35% of the value used in the second case.

Therefore the reduction of $U_{Tp}$ with respect to an isolated neutral network, implies that the reduction of the values of $U_{sg}$ subsequent to the installation of a resonant impedance can be not sufficient to increase the safety of the system.

Moreover, in the resonant earthed neutral systems, the safety conditions must be verified not only for the faulted substation but also, often inside the area related to an unfaulted one, where $U_{sg}$ can be very higher than at the fault location.

On the basis of these considerations it’s easy to understand the importance of studying the interconnection of earthing systems inside MV resonant earthed neutral networks.

Appendix 1

According to Carson’s Theory the following expressions for the impedances $z$, $z^g$ and $z^s$ and for the voltage sources $\bar{E}_{vw,i}^{u,w=a,b,c,s}$, can be written [2]:

- $z = r_c + j \frac{\omega \cdot \mu_o}{2 \cdot \pi} \cdot \ln \frac{2}{0.78d_{oc}}$;
- $z^g = \pi^2 f10^{-4} - j \frac{\omega \cdot \mu_o}{2 \cdot \pi} \cdot \ln \frac{1}{2H_1}$;
- $\bar{E}_{ab,i} = \ell_i \left( j \frac{\omega \cdot \mu_o}{2 \cdot \pi} \cdot \ln \frac{1}{D} \right) \bar{I}_i$;
- $\bar{E}_{ac,i} = \ell_i \left( j \frac{\omega \cdot \mu_o}{2 \cdot \pi} \cdot \ln \frac{1}{D} \right) \bar{I}_i$;
- $\bar{E}_{as,i} = \ell_i \left( j \frac{\omega \cdot \mu_o}{2 \cdot \pi} \cdot \ln \frac{1}{D_m} \right) \bar{I}_i$;
- $\bar{E}_{sa,i} = \ell_i \left( j \frac{\omega \cdot \mu_o}{2 \cdot \pi} \cdot \ln \frac{1}{D_m} \right) \bar{I}_i$;
- $\bar{E}_{sc,i} = \ell_i \left( j \frac{\omega \cdot \mu_o}{2 \cdot \pi} \cdot \ln \frac{1}{D_m} \right) \bar{I}_i$;
being:
- \( r_c \) and \( r_s \) the electric resistance per unit of length of the phase conductor and of the metal sheath respectively;
- \( d_{oc} \) and \( d_{os} \) the diameter of the conductor and the mean diameter of the sheath, respectively;
- \( 2 \cdot H_t = 660 \cdot \sqrt{\rho_c / f} \) the conventional distance between a conductor of the line and the imaginary conductor representing earth, with bulk resistivity \( \rho_c \).
- \( D \) the distance between the phase conductors;
- \( D_m \) the mean distance between the phase conductor and the metal sheath.

**Appendix 2**

For the model of the HV/MV station, represented in figure 5, the following equation can be written:

\[
\begin{align*}
E_b - E_u &= V_{0,f}^{as} - V_{0,f}^{bs} ; \\
E_c - E_b &= V_{0,f}^{bs} - V_{0,f}^{as} ; \\
0 &= V_{0,f}^{as} - V_{0,f}^{sg} - V_{0,u}^{as} + V_{0,u}^{sg} ; \\
0 &= V_{0,f}^{bs} - V_{0,f}^{sg} - V_{0,u}^{bs} + V_{0,u}^{sg} ; \\
0 &= V_{0,f}^{cs} - V_{0,f}^{sg} - V_{0,u}^{cs} + V_{0,u}^{sg} ; \\
k_R \cdot \left( V_{0,f}^{sg} - V_{0,u}^{sg} \right) + (1 - k_R) \cdot I_{0,f}^{s} ;
\end{align*}
\]

\( k_f, k_u \) and \( k_R \) are the status variables of the switches \( S_f, S_u \) and \( S_R \), respectively.

**References**

