

Limitation of Cross Country Fault Currents in MV Distribution Networks by Current Limiting Reactors Connected between Cable Screens and Primary Substation Earth Electrode

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Abstract

MV distribution networks with ungrounded or grounded neutral by compensating impedance are exposed to Cross-Country-Faults (CCFs). If CCFs occur in cable lines, fault current value can reach that of line-to-line fault current. This is because the large part of the fault current flows through cable screens and only a small amount through grounding systems of secondary and primary substations. Cable screens in the joints can reach very high local temperatures where screen and copper stocking connecting the sectioned screens are not pressed enough each other. In these small areas high electric contact resistances cause large joule losses, potentially leading to insulation burning. Successive temporary/switching overvoltages can cause dielectric failure, i.e. faults to ground. A way to prevent the screen insulation thermal damage could be a drastic reduction of CCF currents, especially when they occur in different cable feeders of the MV network. The paper illustrates a countermeasure able to reduce CCF currents: the use of current limiting reactors (CLRs) connecting the cable screens to the earth electrode of the primary substation. The influence of the CLRs on the equivalent earth impedances of primary and secondary substations is investigated. The methodology is applied to an existing MV distribution network.

Keywords: Cross-Country-Fault; Cable Screen; MV Cable Distribution Network; Current Limiting Reactor; Earth Electrode; Equivalent Earth Impedance.

Acronyms

CCF	Cross Country Fault
CL	Cable Line
CLR	Current Limiting Reactor
EE	Earth Electrode
EEI	Earth Equivalent Impedance
ER	Earth Resistance
LGF	Line to Ground Fault
LL	Line-to-Line
OHL	Overhead Line
PS	Primary Substation
SS	Secondary Substation

1 Introduction

Transmission and distribution networks experience Line-to-Ground Faults (LGFs), both as simultaneous and in sequence LGFs; the latter are usually referred as Double Fault-to-Ground or Cross-Country-Faults (CCF). Calculation of CCF currents is required to assess the capacity of cable screens to withstand the large current values that may be caused by such faults [1]-[11]. The operational experience of MV distribution networks, both with compensated and ungrounded neutral, shows that a LGF may cause additional LGFs due to subsequent switching and temporary overvoltages occurring in the healthy phases. If the network neutral is grounded via Petersen coil, also equipped with a parallel high resistance, the Earth-Fault-Factor is 1.73 p.u., whereas in MV networks with ungrounded neutral it can be up to 2.5-3.5 p.u. [12]. On the other hand, in an MV network LGFs yield switching overvoltages larger than 3-4 p.u.: consequently, network components with reduced insulation dielectric strength can experience a second fault to ground.

In CLs, CCFs can occur either between two phases of the same feeder or between two different feeders, as sketched in Fig. 1.

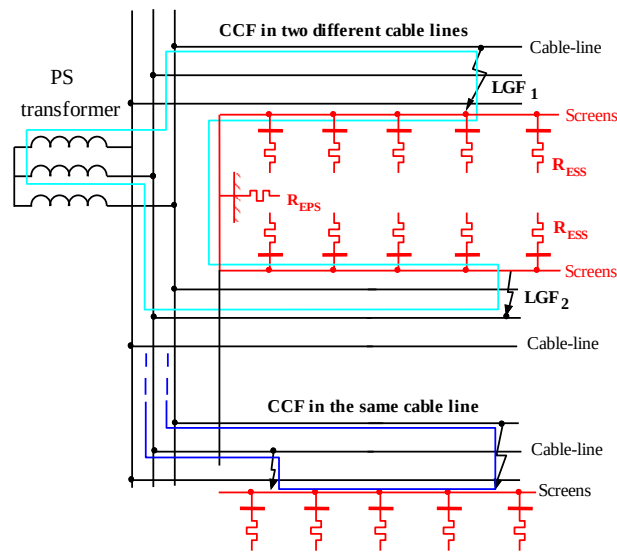


Figure 1 – Possible CCFs occurring in an MV radial network.

If CCF involves only CLs, the fault current flows not only through the earth systems of the secondary and primary substations (SS, PS) but also, and mainly, through the metallic cable screens connected to SS and PS ground electrodes. The evaluation of CCF currents, as well as its share between earth systems and cable screens of the faulty and healthy lines, needs the use of specific software (such as ATP, EMTP, DigSilent, etc.), where each component can be modelled in the phase domain. In particular, detailed models of phase conductors and earth conductors (as cable screens/armours, shield wires, ground wires of overhead/cable lines, counterpoise conductors) are needed: each cable/overhead line segment has to be modelled by the nominal-pi circuit, which accounts series impedance and shunt admittance matrices (Fig.2). In such a way, even though it is possible to simulate the MV distribution mixed cable-overhead networks with high accuracy, the implementation of the whole model in case of extended networks is much elaborated and time consuming.

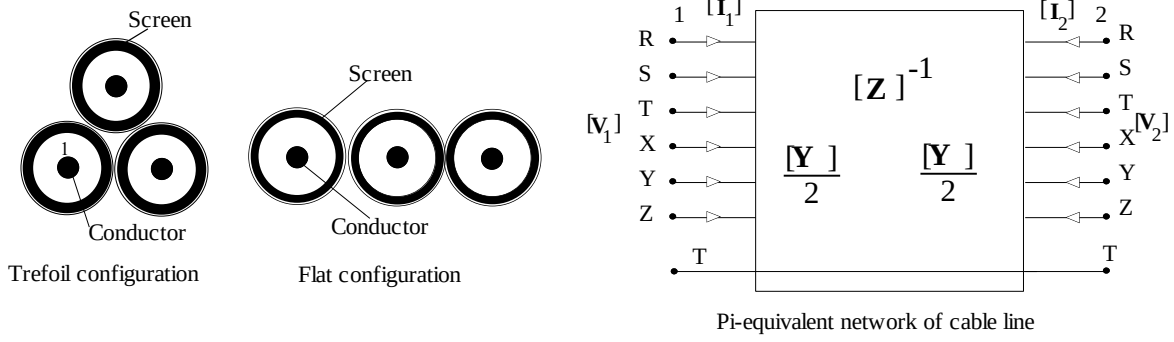


Figure 2 – MV Cable line in trefoil and flat configurations; equivalent Pi-circuit of a cable line with three phase conductors and three metallic screens.

On the other hand, the application of symmetrical components (0, 1, 2) method to calculate asymmetrical faults [1] is rather laborious in case of simultaneous faults: in [9], a simple equivalent circuit and formulas are proposed to evaluate CCFs occurring in overhead lines of a MV distribution networks. Reference [11] presents a time saving model to calculate the steady state behaviour of mixed cable/overhead MV distribution network during CCFs. The model allows evaluating with satisfying accuracy the CCF currents, the currents in cable screens (at fault locations and at PS), as well as the relevant screen voltages to ground and ground potential rise of the earth electrodes. It should be pointed out that, in the worst case, CCF currents involving cable lines are comparable with short circuit current values, since if two LGFs occur near the PS the fault current is practically equal to the line-to-line (LL) fault current I_{LL} :

$$I_{CCF} = I_{LL} = 1.1 \cdot \frac{\sqrt{3}}{2} \cdot \frac{U_n}{Z_{sc} + Z_{IN}} \quad (1)$$

being U_n the network rated voltage, Z_{sc} the leakage impedance of the PS transformer and Z_{IN} the positive sequence HV network impedance. For example, for a typical Italian PS equipped with a 150 kV / 20 kV – 40 / 63 MVA – $U_{sc}=15.5-22.5\%$ transformer, supplied for example by a 3000 MVA - 150 kV subtransmission network, a LL fault close to PS is in the range of 6.5-7.1 kA.

Since such high current value can cause thermal damage in the insulation surrounding the screen/sock in the cable joints, the authors are investigating the following measures to reduce the current flowing in the cable screens during CCF occurring in two different cable lines:

1. Use of CLR s connected between cable screens and earth electrode of PS
2. Disconnection of the cable screens of each cable line from the earth electrode of PS
3. Use of a ground conductor connecting all SSs and PS earth electrodes
4. Disconnection of the screens from the SS earth electrode only at one end of the cable line and use of the ground conductors.

The present paper focuses on the application of CLR s, since it appears the most promising countermeasure because does not require invasive interventions on the distribution network; however, the other three countermeasures will be discussed and compared in future work. Section II deals with the criteria to calculate the reactance values of CLR s. Section III illustrates a method for evaluating the influence of CLR s on the equivalent earth impedance of the PS and SS. Lastly, Section IV reports the main results of the application of CLR s to an existing 20 kV distribution network owned and operated by e-distribuzione, the largest Distribution System Operator in Italy.

2 CLR sizing

It is well known that series reactors can be used to limit the short circuit current values [13]-[16], especially in MV industrial electrical power systems fed by HV network with high short circuit power and, above all, when MV synchronous generators are directly connected [17]-[19]. Based on this application, the authors have investigated the possibility to reduce CCF currents occurring in different MV cable lines by connecting suitable reactors not in series with phase line conductors but between the screens and the earth electrode of PS, as shown in Fig. 3. In such a way, CLR s are installed in the metallic loop of CCF currents, increasing the fault loop impedance and thus reducing the fault current value.

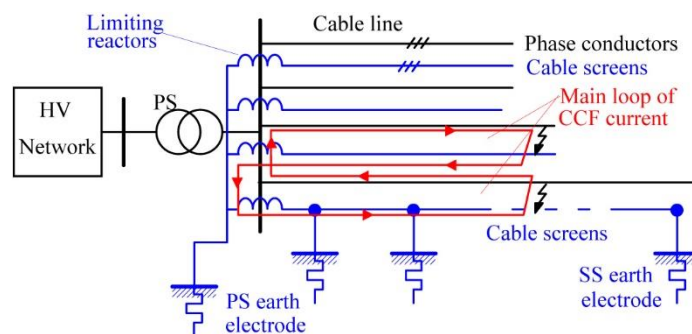


Figure 3 – Main loop of the CCF current occurring in two cable lines.

In order to calculate the suitable values of the CLRs, the two criteria listed below may be considered:

- 1) For the screen current worst case, ensure that CCF current is equally shared between the upstream and downstream screens at fault locations
- 2) For the screen voltage to ground worst case, the maximum voltage between screens and ground at fault locations must be limited to an assigned maximum value.

2.1 Equivalent circuits of the system formed by the three cable screens and the earth resistance of the SS

Methods for evaluating the CLRs and the equivalent earth impedances of the PS and SS need an equivalent circuit of the system formed by the three cable screens and the earth resistances of the SS. The system can be approximated by the homogenous uniformly distributed line in Fig. 4a, where mutual series impedances and capacitances between phase conductors and screens are neglected, as well as the capacitance between screens and ground.

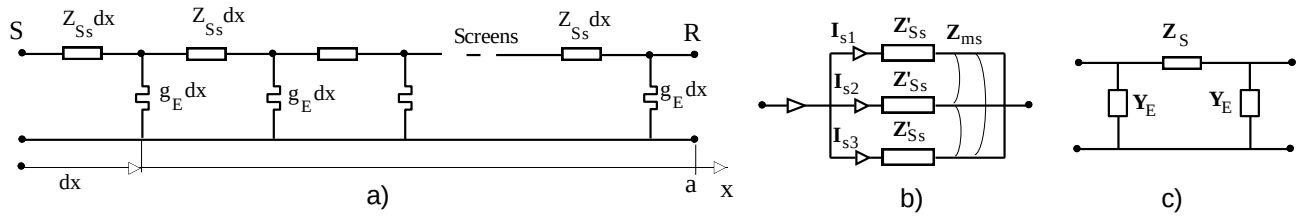


Figure 4 – Equivalent circuits of the system formed by cable screens and earth resistances of SSs.

Symbols in Fig. 4a and Fig. 4b:

- g_E is the average conductance to ground due to earth resistances of the SSs in per unit length: $g_E = 1/(R_{ESS} \cdot d_{ss})$, being R_{ESS} and d_{ss} respectively the average earth resistance of the SSs and the average distance between them;
- Z_{Ss} is the equivalent series self-impedance of the 3 screens, $Z_{Ss} = (Z'_{Ss} + 2Z_{ms})/3$ from Fig.4b;

Posing

$Z_{os} = \sqrt{Z_{ss}/g_E}; K_s = \sqrt{Z_{ss}g_E}; A = \cosh(K_s a); B = Z_{os} \sinh(K_s a); C = \sinh(K_s a)/Z_{os}$, the

impedance and the admittance of the equivalent Pi-circuit of the system formed by the three cable screens and the SS earth resistances, shown in Fig. 4c, are given by:

$$\begin{cases} Z_S = Z_{os} \sinh(K_s a) \\ Y_E = (A-1)/B \end{cases} \quad (2)$$

From the equivalent Pi-circuit in Fig. 4c, the Thevenin impedance at the sending end of the MV cable line is $Z_t = A/C$.

2.2 Calculation of the CLR reactances

In order to find the values of the CLRs fulfilling both the above listed criterion 1) and 2), the worst case must be considered, i.e. the two LGFs occur at the sending end of the two cable lines involving the CCF. Let us refer to the approximate equivalent circuit on the left in Fig. 5, where:

- Z_{eq} is the phase self equivalent impedance given by the upstream HV network in series with the HV/MV transformer;
- X_1 and X_2 account the reactances of the CLRs which have to be calculated;
- Z_{t1} e Z_{t2} are the Thevenin impedances at the sending end of the systems formed by screens and SS earth resistances of each cable lines ($Z_{t1} = A_1/C_1$ and $Z_{t2} = A_2/C_2$, according to Section 2.1);
- R_{EPS} is the earth resistance of the PS.

In the equivalent circuit the series of $X_i - Z_{ti}$ of the remaining cable lines originating from the PS, in parallel to R_{EPS} , have been neglected because they have little influence.

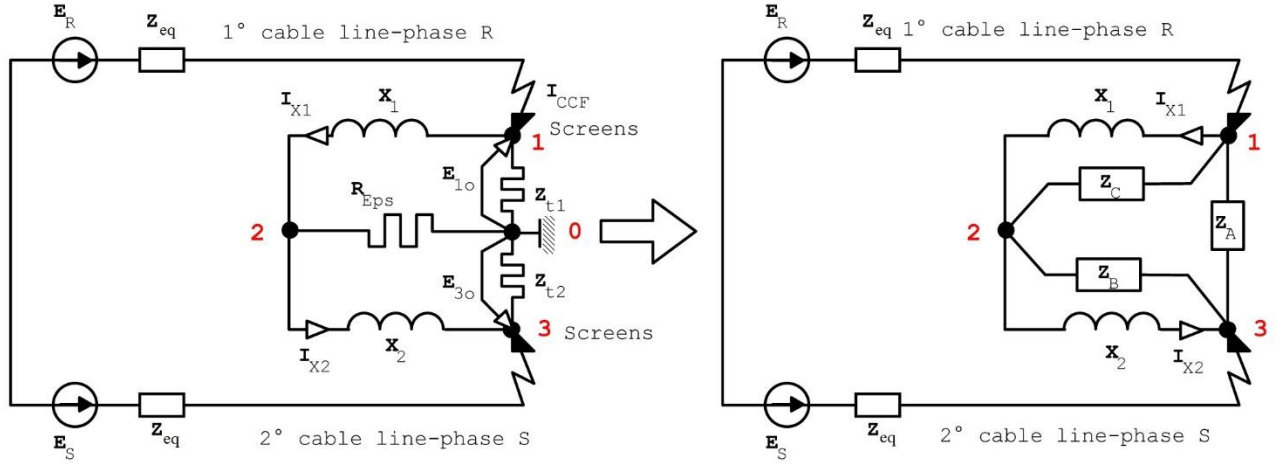


Figure 5 – Approximate equivalent circuit of the two CLs involved by the CCF.

By transforming the star of impedances connected to 1-0, 2-0 and 3-0 to the delta ones, the circuit on the right in Fig. 5 is obtained, where:

$$\mathbf{Z}_A = \mathbf{Z}_{t1} + \mathbf{Z}_{t2} + \frac{\mathbf{Z}_{t1}\mathbf{Z}_{t2}}{\mathbf{R}_{EPS}}; \mathbf{Z}_B = \mathbf{R}_{EPS} + \mathbf{Z}_{t2} + \frac{\mathbf{R}_{EPS}\mathbf{Z}_{t2}}{\mathbf{Z}_{t1}}; \mathbf{Z}_C = \mathbf{R}_{EPS} + \mathbf{Z}_{t1} + \frac{\mathbf{R}_{EPS}\mathbf{Z}_{t1}}{\mathbf{Z}_{t2}}.$$

Posing $\mathbf{Z}_{p12}(\mathbf{X}_1) = \frac{j\mathbf{X}_1\mathbf{Z}_C}{j\mathbf{X}_1 + \mathbf{Z}_C}$ and $\mathbf{Z}_{p23}(\mathbf{X}_2) = \frac{j\mathbf{X}_2\mathbf{Z}_B}{j\mathbf{X}_2 + \mathbf{Z}_B}$, the CCF current can be easily expressed as:

$$\mathbf{I}_{CCF}(\mathbf{X}_1, \mathbf{X}_2) = \frac{\mathbf{E}_R - \mathbf{E}_S}{2\mathbf{Z}_{sc} + \frac{[\mathbf{Z}_{p12}(\mathbf{X}_1) + \mathbf{Z}_{p23}(\mathbf{X}_2)]\mathbf{Z}_A}{\mathbf{Z}_{p12}(\mathbf{X}_1) + \mathbf{Z}_{p23}(\mathbf{X}_2) + \mathbf{Z}_A}} \quad (3)$$

It follows:

$$\mathbf{E}_{13}(\mathbf{X}_1, \mathbf{X}_2) = \frac{\mathbf{Z}_A [\mathbf{Z}_{p12}(\mathbf{X}_1) + \mathbf{Z}_{p23}(\mathbf{X}_1)]}{\mathbf{Z}_{p12}(\mathbf{X}_1) + \mathbf{Z}_{p23}(\mathbf{X}_1) + \mathbf{Z}_A} \mathbf{I}_{CCF}(\mathbf{X}_1, \mathbf{X}_2) \quad (4)$$

and thus the current in the branch 1-2-3, $\mathbf{I}_{123}$, and the voltages $\mathbf{E}_{12}$ e $\mathbf{E}_{23}$ are:

$$\mathbf{I}_{123}(\mathbf{X}_1, \mathbf{X}_2) = \frac{\mathbf{E}_{13}(\mathbf{X}_1, \mathbf{X}_2)}{\mathbf{Z}_{p12}(\mathbf{X}_1) + \mathbf{Z}_{p23}(\mathbf{X}_2)}; \mathbf{E}_{12}(\mathbf{X}_1, \mathbf{X}_2) = \mathbf{Z}_{p12}(\mathbf{X}_1) \mathbf{I}_{123}(\mathbf{X}_1, \mathbf{X}_2);$$

$$\mathbf{E}_{23}(\mathbf{X}_1, \mathbf{X}_2) = \mathbf{Z}_{p23}(\mathbf{X}_2) \mathbf{I}_{123}(\mathbf{X}_1, \mathbf{X}_2).$$

Finally the currents flowing through the CLRs, $\mathbf{I}_{X1}$ and $\mathbf{I}_{X2}$, and the voltages between screens and ground, $\mathbf{E}_{10}$ and $\mathbf{E}_{30}$, are:

$$\begin{cases} \mathbf{I}_{X1}(X_1, X_2) = \mathbf{E}_{12}(X_1, X_2) / jX_1 \\ \mathbf{I}_{X2}(X_1, X_2) = \mathbf{E}_{23}(X_1, X_2) / jX_2 \\ \mathbf{E}_{10}(X_1, X_2) = \mathbf{Z}_{t1} [\mathbf{I}_{CCF}(X_1, X_2) - \mathbf{I}_{X1}(X_1, X_2)] \\ \mathbf{E}_{30}(X_1, X_2) = \mathbf{Z}_{t2} [-\mathbf{I}_{CCF}(X_1, X_2) + \mathbf{I}_{X2}(X_1, X_2)] \end{cases} \quad (5)$$

In (5), $\mathbf{E}_{10}$, $\mathbf{E}_{30}$, $\mathbf{I}_{X1}$ and $\mathbf{I}_{X2}$ are a function of the two unknown reactances X_1 and X_2 , whose values can be calculated by solving the following nonlinear systems, obtained by applying the two criteria proposed, i.e.:

- 1) CCF current equally shared between the upstream and downstream screens at fault locations

$$\begin{cases} \left| \frac{\mathbf{E}_{10}(X_1, X_2)}{\mathbf{Z}_{t1}} \right| = |\mathbf{I}_{X1}(X_1, X_2)| \\ \left| \frac{\mathbf{E}_{30}(X_1, X_2)}{\mathbf{Z}_{t2}} \right| = |\mathbf{I}_{X2}(X_1, X_2)| \end{cases} \quad (6)$$

- 2) maximum voltage between screens and ground at fault locations limited to an assigned maximum value, $V_{\max}$

$$\begin{cases} V_{\max} = |\mathbf{E}_{10}(X_1, X_2)| \\ V_{\max} = |\mathbf{E}_{30}(X_1, X_2)| \end{cases} \quad (7)$$

3 Equivalent earth impedance of the Primary and Secondary Substations

In public radial MV distribution networks, earth electrodes installed at PSs, SSs and HV overhead line towers are generally connected each other by the MV and HV cable screens, by the HV line shield wires and by ground wires (Fig. 6). This earth framework, called Global Earth System, makes the equivalent earth impedance of PSs and SSs very low, much smaller than each earth resistance of the SSs, PS and HV line towers.

In order to estimate EEIs of PS and SS with acceptable accuracy, at least the earth resistance of PS and the system formed by the cable screens with the ER of SSs should be taken into account, as shown in Fig 7. The screens-SS earth resistances system of each cable line can be represented by

the equivalent circuit derived in Section 2.1. Fig. 7 hence refers to the calculation of the SS earth equivalent impedance of a “b+a” km long cable line, at an “a” km distance from the PS.

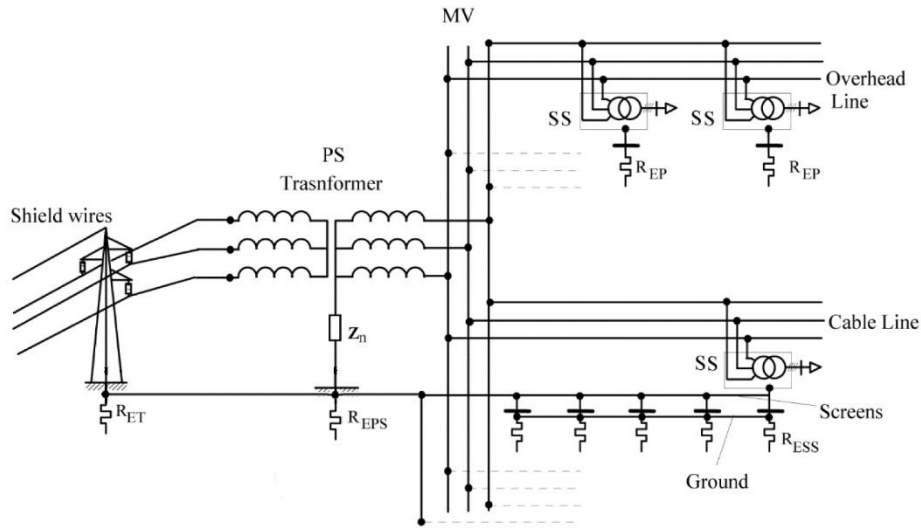


Figure 6 – Schematic representation of the Global Earth System.

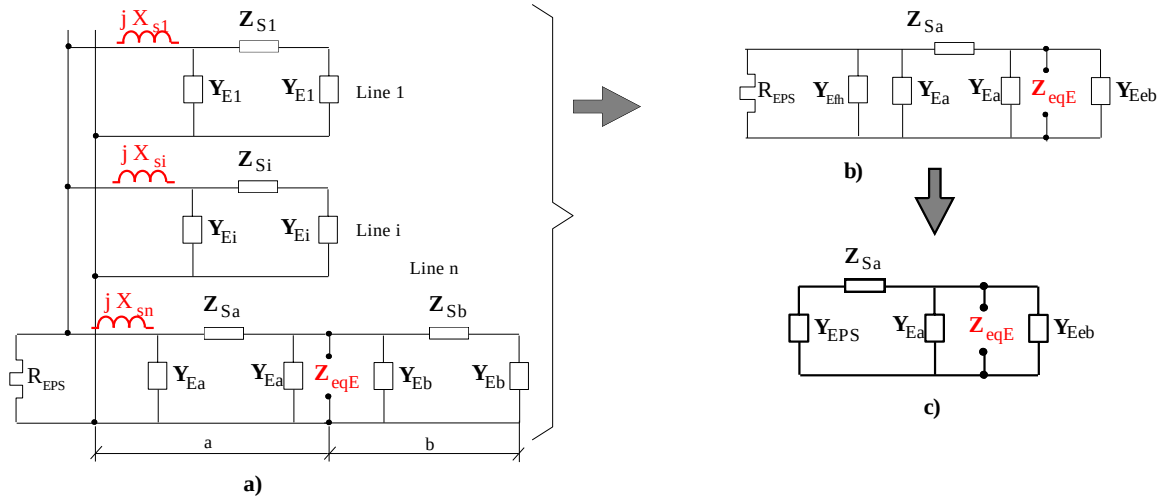


Figure 7 – Equivalent circuit of the Global Earth System of an HV/MV network.

Symbols in Fig. 7:

- Z_{Sa} , Y_{Ea} , Z_{Sb} , Y_{Eb} , are the impedances/admittances of the Pi-circuits attendant to the two line sections “a” and “b”, computed with (2);
- Z_{Si} , Y_{Ei} are the relevant impedance/admittance of the Pi-circuits of the others n-1 cable lines.
- R_{EPS} is the earth resistance of the PS;

- Y_{Efh} in Fig. 7b is the parallel of the Thevenin admittances of n-1 remaining cable lines:

$$Y_{Efh} = \sum_{i=1}^{n-1} Y_{Ephi} = \sum_{i=1}^{n-1} \frac{\sin(K_{si} L_i)}{Z_{os} \cosh(K_{si} L_i)};$$

- $Y_{Eeb} = \frac{\sin(K_{sn} b)}{Z_{osn} \cosh(K_{sn} b)}$

Setting $Y_{EePS} = \frac{1}{R_{EP}} + Y_{Efh} + Y_{Ea}$, the equivalent earth impedance of the SS is thus given by:

$$Z_{eqSS} = \left[\frac{1}{Z_{Sa} + 1/Y_{EaPS}} + Y_{Ea} + Y_{Eeb} \right]^{-1} \quad (8)$$

From (8) it follows that the equivalent earth impedance of SS:

- is not a resistance but an inductive-resistive impedance;
- is a function of the location of the SS along the cable line: the closer it is to the PS the smaller the impedance is, and more similar to a pure resistance.

If CLRs (whose reactance is X_{Si} in Fig. 7) are connected between each cable screen and the earth electrode of the PS, the following corrected expressions for Y_{Efh} and Y_{EePS} may be used:

$$Y_{Efh} = \sum_{i=1}^{n-1} Y_{Ephi} = \sum_{i=1}^{n-1} \left(jX_{si} + \frac{Z_{os} \cosh(K_{si} L_i)}{\sin(K_{si} L_i)} \right)^{-1} \quad (9)$$

$$Y_{EePS} = \left[\left(\frac{1}{R_{EPS}} + Y_{Efh} \right)^{-1} + jX_{sn} \right]^{-1} + Y_{Ea} \quad (10)$$

4 Use of CLRs on an existing 20 kV MV distribution network

4.1 CCFs in cable lines without use of CLRs

In order to verify the effects of CLRs on the CCF current and on the equivalent earth impedances of the PS and SS, an existing Italian 20 kV MV distribution network, owned by e-distribuzione, has been taken as case study. The one line diagram of the network is reported in Fig. 8.

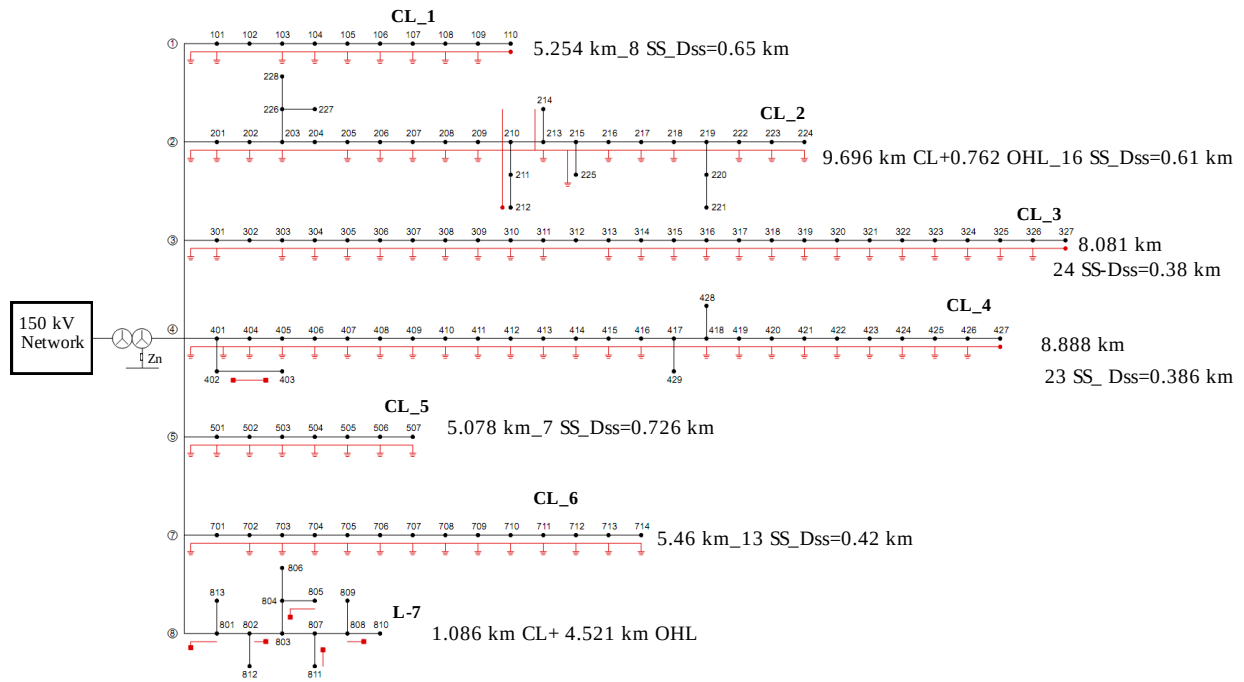


Figure 8 – HV/MV-20 kV existing radial distribution network considered in the study.

The length of each line is reported in Fig. 8, together with its composition (CL or overhead line, OHL); the network extension is about 48 km, of which about 43.5 km are CLs. CLs are equipped with 50-95 mm²-Cu, 150-185-240 mm²-Al conductors; in all cases, cable screens are made of copper with 16 mm² cross section. OHLs are equipped with 16-25-35 mm²- Cu conductors. In the PS, a 40 MVA, 150/21.6 kV transformer is installed, with $u_{sc}=0.155$ p.u., $P_{cu}=155$ kW and $P_0=21.5$ kW; the zero sequence transformer magnetizing impedance, Z_{00} , is 0.8 p.u., whereas resistance and reactance values of the compensating impedance are $R_n=400 \Omega$ and $X_n=120 \Omega$, respectively. Short-circuit power at the 150 kV supply bus has been assumed infinite.

A detailed ATP-EMTP model of the system has been implemented, modelling all CL stretches between each SS by 6x6 Pi-circuits with intermediate sections. Cable screens are connected to the earth electrodes of PS and SSs. The PS earth resistance has been assumed equal to 1 Ω ; two different values for the earth resistance of each SS and MV OHL pole have been assumed, [1, 30] Ω and [10, 100] Ω , respectively. For each different combination of earth resistances, all CCFs between two network nodes have been simulated, considering two different neutral network earthing, i.e. ungrounded and grounded by compensating impedance.

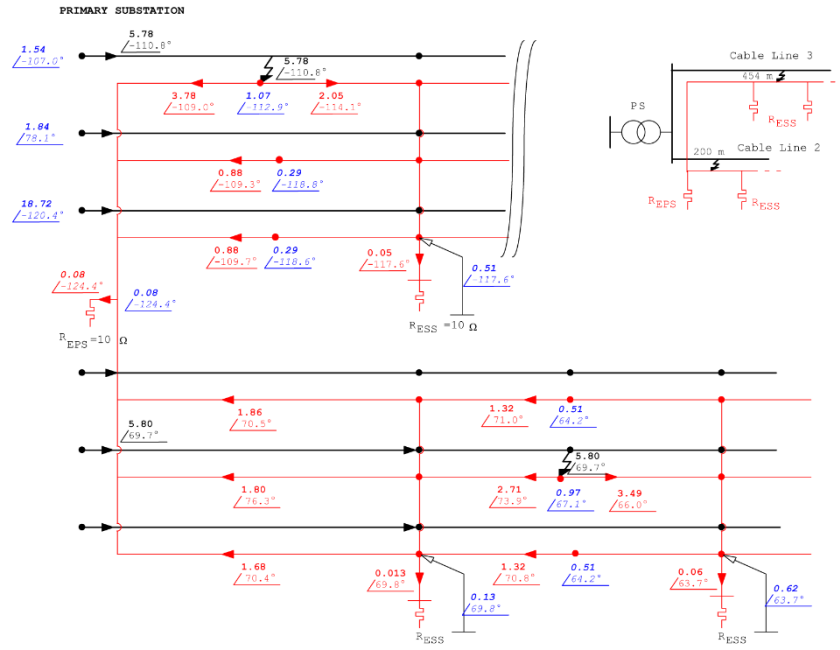


Figure 10 – Voltages (blue) and currents (red) for a CCF occurring in CL2 and CL3 of the studied network.

4.2 CCFs in CLs with CLR installed

For the studied network, the connection of CLR between the screens of each CL and the PS earth electrode has been considered. The values of CLR have been calculated, for each pair of cable lines, according to the criteria proposed in Section 2, considering the length, the number of SSs and the average distance between SSs (D_{ss} , reported in Fig. 8). SS and PS earth resistances have been assumed 10Ω and 1Ω , respectively.

a. CCF current equally shared between upstream and downstream screens at fault locations

Table 1 reports the reactance of CLR calculated in such a way to share equally the CCF current between upstream and downstream screens at fault location. Calculation has been performed for every combination of CCFs among the six CLs.

CL	1	2	3	4	5	6
	X_{CLR} [Ω]	X_{CLR} [Ω]	X_{CLR} [Ω]	X_{CLR} [Ω]	X_{CLR} [Ω]	X_{CLR} [Ω]
1	-	2.20	1.64	1.75	2.46	1.81
2	2.32	-	1.66	1.78	2.48	1.84
3	2.32	2.23	-	1.78	2.58	1.84
4	2.32	2.23	1.66	-	2.48	1.84
5	2.29	2.19	1.63	1.74	-	1.80
6	2.31	2.10	1.67	1.77	2.48	-

Table 1 – Calculated CLR reactance equally sharing the CCF current between upstream and downstream screens at fault locations.

It can be highlighted that, for each CL, the required CLR reactances are practically equal to the Thevenin impedance of the system formed by cable screens and earth resistance of SSs. This is due to the very low value of the earth resistance of PS and, consequently, Z_t and the reactance of CLRs are practically in parallel.

b. Maximum voltage between screens and ground at fault locations limited to 5 kV

Applying this criterion for each pair of cable lines, CLR reactance values obtained are reported in Table 2. It can be noted that, also applying this criterion, the values of the required reactances for each CL are within a narrow range.

If voltages between screens and ground must be lower than $V_{\max}=5$ kV for any pair of CCFs, for each CL the smaller X_{CLR} value amongst the ones reported in Table 2 has to be chosen. These values are reported in Table 3, together with X_{CLR} values required by applying the criterion of the current equally shared between upstream and downstream screens at fault locations.

LGF1 location	LGF2 location	LGF1 location	LGF2 location	LGF1 location	LGF2 location	LGF1 location	LGF2 location	LGF1 location	LGF2 location
CL-1 $X_{CLR}=2.50$ Ω	CL-2 $X_{CLR}=2.67$ Ω	CL-2 $X_{CLR}=2.67$ Ω	CL-1 $X_{CLR}=2.50$ Ω	CL-3 $X_{CLR}=4.53$ Ω	CL-1 $X_{CLR}=2.28$ Ω	CL-4 $X_{CLR}=3.85$ Ω	CL-1 $X_{CLR}=2.33$ Ω	CL-5 $X_{CLR}=2.29$ Ω	CL-1 $X_{CLR}=2.51$ Ω
CL-1 $X_{CLR}=2.28$ Ω	CL-3 $X_{CLR}=4.53$ Ω	CL-2 $X_{CLR}=2.67$ Ω	CL-3 $X_{CLR}=4.62$ Ω	CL-3 $X_{CLR}=4.62$ Ω	CL-2 $X_{CLR}=2.67$ Ω	CL-4 $X_{CLR}=3.91$ Ω	CL-2 $X_{CLR}=2.52$ Ω	CL-5 $X_{CLR}=2.31$ Ω	CL-2 $X_{CLR}=2.71$ Ω
CL-1 $X_{CLR}=2.33$ Ω	CL-4 $X_{CLR}=3.85$ Ω	CL-2 $X_{CLR}=2.52$ Ω	CL-4 $X_{CLR}=3.91$ Ω	CL-3 $X_{CLR}=4.24$ Ω	CL-4 $X_{CLR}=3.20$ Ω	CL-4 $X_{CLR}=3.20$ Ω	CL-3 $X_{CLR}=4.24$ Ω	CL-5 $X_{CLR}=2.11$ Ω	CL-3 $X_{CLR}=4.60$ Ω
CL-1 $X_{CLR}=2.51$ Ω	CL-5 $X_{CLR}=2.29$ Ω	CL-2 $X_{CLR}=2.71$ Ω	CL-5 $X_{CLR}=2.31$ Ω	CL-3 $X_{CLR}=4.60$ Ω	CL-5 $X_{CLR}=2.11$ Ω	CL-4 $X_{CLR}=3.91$ Ω	CL-5 $X_{CLR}=2.16$ Ω	CL-5 $X_{CLR}=2.16$ Ω	CL-4 $X_{CLR}=3.91$ Ω
CL-1 $X_{CLR}=2.23$ Ω	CL-6 $X_{CLR}=3.56$ Ω	CL-2 $X_{CLR}=2.52$ Ω	CL-6 $X_{CLR}=3.62$ Ω	CL-3 $X_{CLR}=4.24$ Ω	CL-6 $X_{CLR}=3.27$ Ω	CL-4 $X_{CLR}=3.61$ Ω	CL-6 $X_{CLR}=3.34$ Ω	CL-5 $X_{CLR}=2.16$ Ω	CL-6 $X_{CLR}=3.61$ Ω

Table 2 – Calculated CLR reactance values setting to 5 kV the maximum voltage between screens and ground at fault locations.

Criterion	CL-1 X_{CLR} [Ω]	CL-2 X_{CLR} [Ω]	CL-3 X_{CLR} [Ω]	CL-4 X_{CLR} [Ω]	CL-5 X_{CLR} [Ω]	CL-6 X_{CLR} [Ω]
$V_{\text{screen}}=5$ kV	2.23	2.52	4.24	3.20	2.11	3.27
$I_{\text{screen}}=I_{\text{CCF}}/2$	2.31	2.10	1.67	1.77	2.48	1.80

Table 3 – Value of CLRs obtained applying the two proposed criteria.

Considering CLR reactance values reported in the first row of Table 3, values of CCF current, currents flowing in the screens and maximum screen voltages to earth are shown in Table 4. CCF currents decrease from 5.81 kA to 3.65 kA (37.3% reduction) and voltages between screens and ground are always lesser than 5 kV. The maximum current in the screens decreases to about 2.30 kA, a value significantly lower than the 5.52 kA CCF current flowing in the screens towards the PS in absence of CLRs, in the case of CCF occurring in two different CLs near the PS.

LGF ₁ location	LGF ₂ location	I _{CCF} [kA]	V _{max1,screen} [kV]	V _{max2,screen} [kV]	I _{screen} [kA]	I _{screen} [kA]
CL1	CL2	3.57	4.83	4.74	2.17	2.09
CL1	CL3	3.64	4.97	4.94	2.02	1.32
CL1	CL4	3.61	4.94	4.90	2.03	1.52
CL1	CL5	3.54	4.80	4.87	2.19	2.27
CL1	CL6	3.56	4.94	4.90	2.05	1.66
CL2	CL3	3.65	4.87	4.93	1.93	1.31
CL2	CL4	3.62	4.84	4.90	1.96	1.52
CL2	CL5	3.56	4.71	4.86	2.11	2.27
CL2	CL6	3.61	4.84	4.89	1.97	1.63
CL3	CL4	3.69	5.00	5.00	1.21	1.38
CL3	CL5	3.62	4.91	5.00	1.33	2.11
CL3	CL6	3.68	5.00	5.00	1.23	1.48
CL4	CL5	3.59	4.98	4.88	1.54	2.14
CL4	CL6	3.65	4.97	4.97	1.43	1.51
CL5	CL6	3.58	4.87	4.98	2.15	1.64

Table 4 – CCF current, voltages between screen and ground, and screen currents (rms values).

In order to check results obtained by the proposed approximated methodology, simulations have been performed by using the detailed ATP-EMTP model described in Section 4.1. In particular, a CCF has been simulated at the beginning of both CL2 and CL3, with CL screens connected to the PS earth electrode by means of CLRs with X_{CLR} equal to 2.52 Ω and 4.24 Ω , respectively for CL2 and CL3, as calculated by the approximated methodology (see Table 3). Voltages and currents calculated by ATP are reported in Fig. 11.

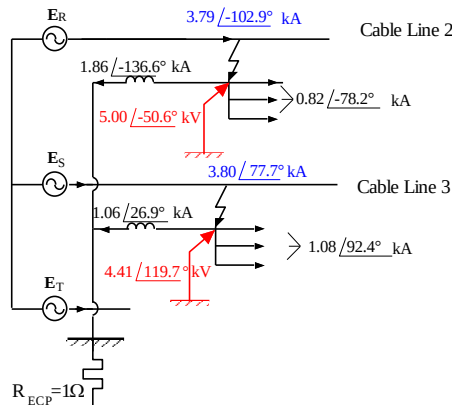


Figure 11 – Voltages and currents calculated by the ATP model for a CCF at the sending ends of CL2 and CL3 of the studied network equipped with CLRs.

The values calculated with both the approximate and ATP model are reported in Table 5. The comparison of the obtained results shows that the proposed simplified network models allow calculating with acceptable accuracy the inductive reactance needed to meet the proposed criteria.

Model	I_{CCF} [kA]	$V_{max1,screen}$ [kV]	$V_{max2,screen}$ [kV]	$I_{screen1}$ [kA]	$I_{screen2}$ [kA]
Approximated (Fig.4)	3.65	4.87	4.93	1.93	1.31
ATP	3.80	5.00	4.41	1.86	1.06

Table 5 – Calculated voltages and currents with both the approximated and ATP model for a CCF at the sending end of CL2 and CL3.

Moreover, it has been verified that CLRs do not reduce the CCF currents at the end of each pair of lines at values so low that the line protection against CCF may fail or misoperate. For example, in case the CCF occurs at the end of CL2 and CL3 of Fig. 8, fault currents are 2.58 kA and 2.63 kA respectively.

4.3 Effect of CLRs on the equivalent earth impedance of the PS and SS

Since CLRs of each cable line are connected between screens and PS earth electrode, they have an impact on the Global Earth System, influencing not only the EEI of PS but also those of SSs. For this reason, the EEI of SSs have been calculated for CL2 of the network in Fig. 8 by using the proposed formula (8), with and without the presence of CLRs in all cable lines (in case CLRs are installed, X_{CLR} values are the ones reported in Table 3 for the maximum admissible voltage criterion). The following parameters have been assumed:

- CL length=8.8 km;
- average distance between SSs $D_{ss}=0.61$ km;
- earth resistance of SSs $R_{ESS}=10 \Omega$;
- earth resistance of the PS $R_{EPS}=1 \Omega$;
- screen self-impedance $Z_{ss}=1.365+j 0.689 \Omega/\text{km}$;
- mutual impedance between screens $Z_{ms}= 0.049+j 0.644 \Omega/\text{km}$.

Fig. 12a and Fig. 12b plot the EEI values of the SSs, Z_{ESS} , versus the SS distance from PS, and its components X_{ESS} and R_{ESS} , without and with CLR, respectively.

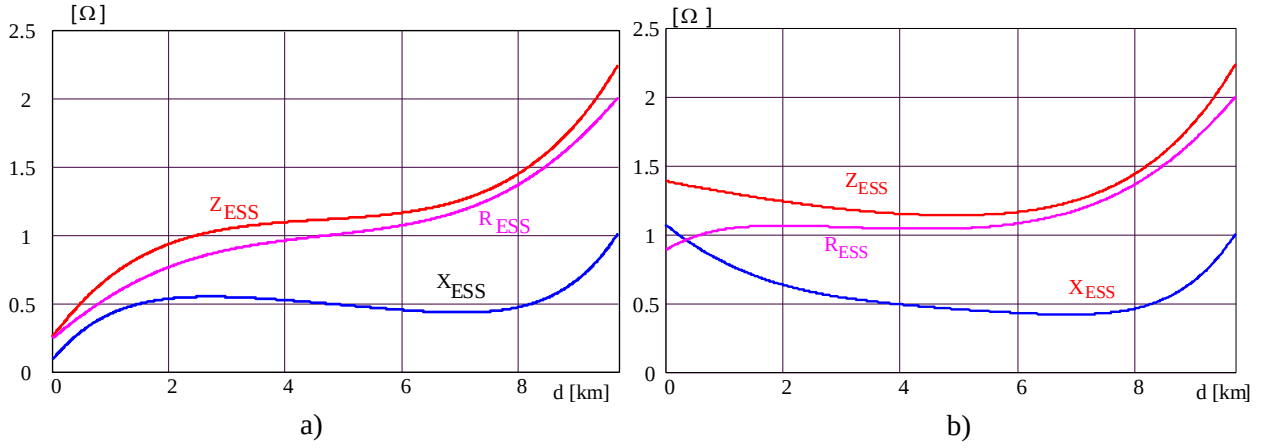


Figure 12 – Earth equivalent impedance, and its resistive and inductive components, of the SSs versus the distance from the PS: a) screens directly connected to the PS earthing; b) screens connected to the PS earthing by CLR.

From Fig.12a and Fig. 12b it is immediately apparent that the EEI of SSs is basically a resistance, except for SSs close to PS when CLR is installed (as shown in Fig. 12b). Without CLR (Fig. 12a), Z_{ESS} increases as the distance from the PS increases. The SSs close to the PS take advantage from the nearby low ER of the PS. The SSs further away from the PS benefit less from the ER of PS, because the interposed screen self-impedance is higher. Despite everything, SSs at the end of the line presents a EEI reduction of 75% with respect to its ER (2.5 Ω compared to 10 Ω); also the EEI of the PS benefits from the presence of the SS ERs, as its value is around 0.25 Ω , 25% of its ER. The CLR connection (Fig. 12b) causes the EEI increase for SSs located up to about 5 km from the PS, the largest increase (1.4 Ω against 0.25 Ω) being associated to the SSs nearest to the PS, even if in this case EEI is only 14% of the SS ER (1.4 Ω against 10 Ω). Moreover, as expected the EEI of the PS, while growing, is lesser than its ER (0.483 Ω against 1 Ω).

Lastly, to appreciate better the effect of CLR on the EEI of the SSs, Fig. 13 shows Z_{ESS} trend versus the distance from the PS, with and without CLR, as well as in the case where screens are supposed disconnected to the PS earth. In the latter case, the SSs with largest EEI are those at

sending and receiving end of the line (2.3Ω), while the SSs located in the midpoint have the smallest EEI (1.6Ω).

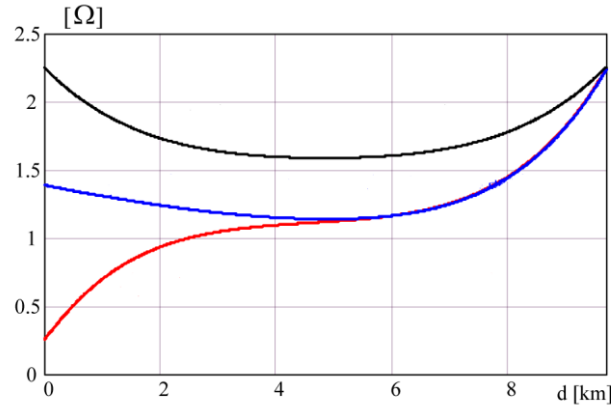


Figure 13 – Earth equivalent impedance trend versus distance d from PS. Black line: screens disconnected from PS earth; blue line: screens connected to PS earth through CLRs; red line: screens directly connected to PS earth.

4.4 Preliminary cost/benefit analysis

A preliminary costs /benefits analysis, to drive the network investments and development, supporting the final decision where to implement and install the Current Limiting Reactors, can be applied based on the following criteria:

$$N_i = \frac{C_{CLRs}}{C_{junction} + C_{manpower} + C_{p\&p}} \quad (11)$$

C_{CLRs} is the total cost of CLRs to install in the PS, $C_{junction}$ is the total cost of cable joints, $C_{manpower}$ is the equivalent cost of manpower for cable joint installation. $C_{p\&p}$ is the average cost due to penalties for a permanent fault, calculated considering an average number of disconnected LV customers and an average duration for each permanent fault and evaluated at national level (for the case study in the paper the rules established by the Italian Energy Authority are taken into account). N_i represents the total number of interruptions causing cable joint failures for which the equality of costs is reached. The PSs and the part of the distribution grid where installation of CLRs is more convenient can be selected considering the network more stressed; i.e. where $N_{CCF} > N_i$, being N_{CCF} the occurred number of Cross Country Faults causing cable joint failure. Considering the actual

economic values in Italy, it is possible to normalize with respect to C_{CLRs} : assuming $C_{CLRs}=1$, other costs are $C_{junction}=0.0017$, $C_{manpower}=0.02$ and $C_{p\&p}=0.067$.

5 Conclusions

Cross Country Fault in MV distribution cable lines may cause high fault currents, up to the line-to-line fault current. The attendant currents flowing in the screens of cable joints are able to increase the insulation temperature in case of high contact resistance between metallic sock and screen. Such high local temperatures can be as high as to cause micro-burning of the insulation. Repetitive cross country faults can amplify the phenomenon so that switching or temporary overvoltages due to a fault, or simply the rated power frequency voltage may cause electric discharges resulting in a line to ground fault followed by permanent trip of the cable line.

The paper describes a mean to reduce the cross country fault current value by connecting suitable current limiting reactors between cable screens and earth electrode of the primary substation. Two criteria are proposed to size the current limiting reactor reactances:

- 1) cross country fault current equally shared between upstream and downstream screens at fault locations;
- 2) maximum voltage between screens and ground at fault locations limited to an assigned value.

The proposed methodology has been applied to an existing Italian 20 kV network, owned by e-distribuzione, showing that the required reactance values of the current limiting reactors are in the range of $[2-4] \Omega$, not able to change substantially the equivalent earth impedance of primary and secondary substations, i.e. not affecting significantly the Global Earth System. Preliminary designs have been carried out, showing that current limiting reactors in the range $[2-4] \Omega$ may be air-core, thus having a linear behavior, and at the same time with not excessive dimensions (length in the range 0.5-0.7 m; width in the range 0.5-0.7 m, height about 0.6 m), thus allowing their installation in the primary substation.

Further studies are under way to analyse the dynamic response of the MV network during cross country faults and to explore other methods for reducing the attendant currents, such as:

- disconnection of the cable screens from the earth electrode of primary substation;
- use of ground conductors connecting, in parallel with the cable screens, all earth electrodes of each secondary substations with the primary substation.

Based on results obtained in the study reported in this paper, the authors and e-distribuzione have planned to install current limiting reactors in the studied 20 kV network, in order to verify the actual response of the system during CCFs by a measurement campaign.

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