IMPACT OF THE CABLES' SHIELDS DISCONNECTION ON THE THERMAL STRESS REDUCTION IN CASE OF CROSS-COUNTRY FAULTS

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ABSTRACT

During a fault event, in particular for a multiphase failure with ground, the highly increased currents generate a relevant stress on the insulation layers of the MV cables. Since the dissipated power is proportional to the squared value of the fault current, any attempt to limit the fault current, let alone the persistence time, may reduce the stress on the insulation layers, thus allowing a longer expected life of the cable itself.
This paper analyses the possible benefits associated with the disconnection of the cable's shields at the primary substation end, evaluating, throughout a specifically designed algorithm, the average thermal stress, as well as the life reduction, associated to a cross-country fault (CCF).
This analysis is then further supported by a statistical evaluation that underlines the impact of the shield's connection on the average number of CCF on the e-distribuzione's network.

INTRODUCTION

The connection of MV cables' shields, at HV/MV substation earth system, is a possibility offered by the European standard EN 50522 "Power installations exceeding 1 kV a.c. (1,5 kV d.c.)" [1]. This solution allows the reduction of the fault loop impedance, introducing a significant attenuation of the equivalent earth current flowing through the earth system during the fault, limiting the associated potential rise. Besides, the cable shields' connection at the primary substation determines a relevant reduction of the overall fault loop impedance, thus increasing the resultant cross-country faults' current value.

e-distribuzione, the main Italian DSO, currently operates over 25'000 MV lines all across Italy, with regards these lines, three different connection methods of the MV shields are allowed on the network:

- Shields directly connected to the primary substation's earth network
- Shields connected through the interposition of an insulation joint
- Shields disconnected and individually insulated

The pictures below show the three mentioned connection possibilities:

Figure 1 - Possible connection of the cable's shields. From left: 1) disconnected – 2) connected – 3) with insulation joint

In order to experimentally evaluate the benefit associated with cable's shields disconnection at the primary substation, e-distribuzione launched in 2014 an experimental campaign in 84 substations whose cable's shields where historically connected to the earth network and that were characterized by multiple CCF.

CCF IDENTIFICATION

In order to identify cross-country faults, a specific procedure has been implemented to recognize and collect all the data needed.
To classify a fault as a cross-country one, the following conditions must occur:

- Two distinct events occurred in a 30 seconds time frame within the same primary substation and characterized by:
  - A tripping record with a 67.3 or 51.3 event OR
  - A tripping record with a 67.3 and 51.2/51.3 event

With the aim to obtain a relevant database, all the protection events with the above characteristics occurred in the period between 2012 and 2015 have been taken into account, generating a statistically relevant database of 1780 CCF events.

EVALUATION OF FAULT CURRENT

During a CCF the overall fault current may reach peak values of up to thousands of kA since the impedance loop is mainly constituted by a metallic path. Using the superposition effect, the fault current may be split into two independent components: a first one influenced by the fault loop of the primary substation, and a second one, influenced by the fault loop of the secondary substation.

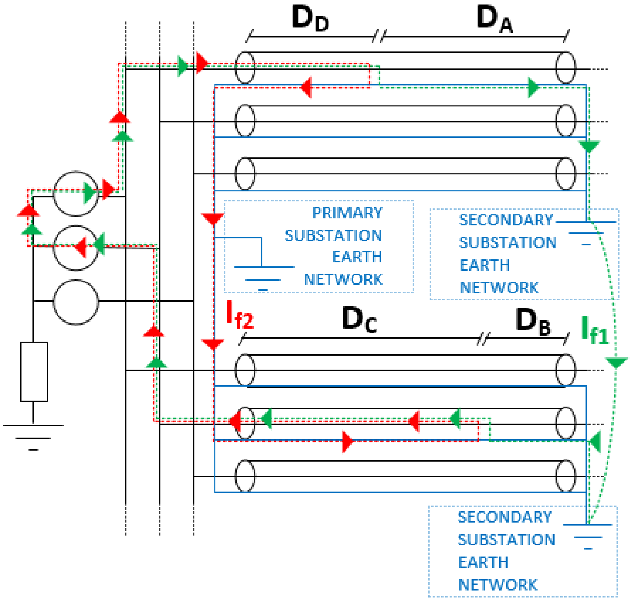

Figure 2 - Typical CCF loop

The main components of these two loops can be listed as follows.
For the first component (I_{f1}), whose path includes the secondary substation:

- the equivalent impedance generated by the affected portion of the cables' shields
- the secondary substation earth longitudinal equipment
- the transformer windings, and the faulted phases

For the second component (I_{f2}), whose path includes the primary substation:

- the affected portion of cables' shields
- the primary substation earth equipment
- the transformer and the faulted phases

Since the second component, I_{f2}, does not flow into the earth electrodes, depending on the fault position, this component may be much greater than the first one. ($I_{f2} >> I_{f1}$)
By disconnecting the primary substation side of the cables' shields, I_{f2} may be reduced to a negligible value, while at the same time, as remarked by the superposition effect, I_{f1}'s value is not altered.
With this approach the electro-thermal stress on the cables' insulation, as well as on all the other equipment involved, may be drastically reduced, allowing a longer expected life.
The relationships between the fault currents and the network parameters can then be identified by the following equations:

$$I_{f1} = \frac{V}{R_{G1}+Z'_{sh}\cdot D_A+R_{tCS1}+R_t+R_{tCS2}+Z'_{sh}\cdot D_B+R_{G2}+Z'_f\cdot D_C+2\cdot Z_{tr}+Z'_f\cdot D_D} \quad (1)$$

$$I_{f2} = \frac{V}{R_{G1} + Z'_{sh} \cdot D_D + Z'_{sh} \cdot D_C + R_{G2} + Z'_f \cdot D_C + 2 \cdot Z_{tr} + Z'_f \cdot D_D} \quad (2)$$

Where:
R'_{tCS1} = Earth resistance of the first secondary substation
R'_{tCS2} = Earth resistance of the second secondary substation
Z'_f = Per unit impedance of the MV line's phase
Z_{tr} = Equivalent impedance of the transformer's windings
Z'_{sh} = Per unit impedance of the cable's shield
R_{G1} = Fault resistance of the first earth fault
R_{G2} = Fault resistance of the second earth fault
R_t = Equivalent resistance of the earth path
$V = \sqrt{3}\, E$ = phase to phase voltage

FAULT CURRENT'S SIMULATION

In order to evaluate the possible benefits associated with the shield's disconnection program, all the 1780 (CCF) interruptive events have been considered. For all of these events the network parameters were extrapolated from the database.
For each event, the following pieces of information have been taken into account:

- Fault typology
- Electrical distance of the first fault from the MV bus-bar
- Electrical parameters of the faulted network

Since the electrical distance of the fault was known regarding only the first fault event, the following assumptions have been made:

- The electrical distance of the first fault was assumed as the sum of all the lengths of the branches/segments up to the first fault point
- An electrical distance equals to zero was considered for the second fault, assuming then the distance from the MV bus-bar to the secondary substation earth electrode equal to electrical distance of the first fault ($D_d = D_b$)

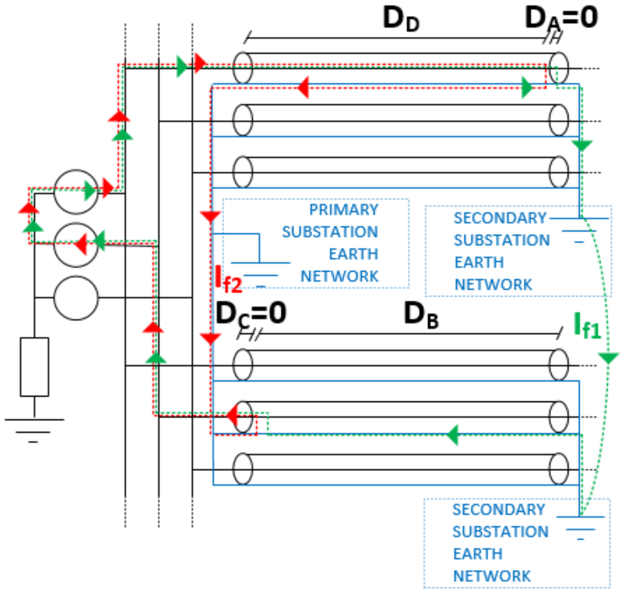

Figure 3- Considered fault loop (CCF)

Whenever the length of the over head line (OHL) of the faulted line represents more than 10% of the overall line's length, the fault path has been considered including the interposition of two earth electrodes as visible in figure 4.

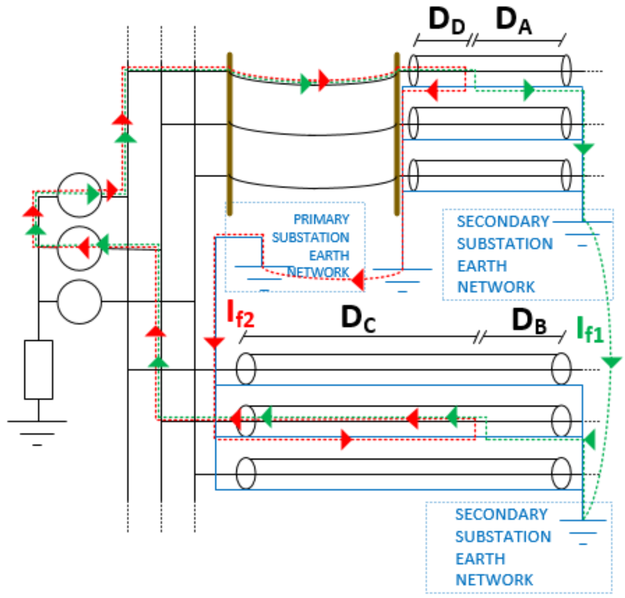

Figure 4 - Fault loop involving an OHL

CALCULATION OF THE PARAMETERS

HV/MV Transformers

The equivalent impedance of the transformers has been calculated using the suppliers' datasheets. These values, which may vary according to the nominal power output of the unit, vary from a maximum value of 2.81Ω to a minimum of 1.46Ω, corresponding to the 12 and 63 MVA units respectively.

Cable's impedance

In order to evaluate the phase's impedance of the faulted line, the main sections of the affected branches have been taken into account.

With regards the MV lines, e-distribuzione has used over the years up to ten different cable's sections:

- Copper: 50, 95, 120, 150 mm^2
- Aluminum: 70, 95, 120, 150, 185, 240 mm^2

For each fault event the appropriate equivalent section has been taken into account, the corresponding impedance's value was then increased to consider also the effect of the operating temperature, which was assumed as 90°C.

Shield's impedance

With regards the impedance of the shields, for each cable's typology, the correspondent shield's cross-section has been evaluated, obtaining then the equivalent impedance. These values were then increased to consider the effect of the operating temperature that, as suggested by the international standards, has been assumed equals to 60°C.

Phase Section (mm$_2$)	Shield's impedance Z (Ω/km)
50	1,442
70	1,313
95	1,301
120	1,172
150	0,738
185	1,137
240	0,645

Table 1 - Typical shield's impedance values with respect to the respective phase cross-section

Earth electrodes

According to the relevant standards, a resistance of 1.6 Ω has been taken into account. This value represents the maximum admissible value for a secondary substation's electrode.

Fault extinction time

The equivalent time in which a fault may persist on the cable has been evaluated considering the typical time of a fault extinction cycle of the protection system, taking into account the following coordination time:

Event	Time
First fault event	250 ms + 70 ms
Second fault event (after first reclosure)	100 ms + 70 ms

Table 2 - Typical fault extinction cycle

The sum of these individual times represents the overall persistence time of the fault, equals to 490 ms. Since the cycle is completed in a limited amount of time, the thermal dissipation of the cable has been neglected, assuming then an adiabatic event.

THERMAL STRESS EVALUATION

A first evaluation of the thermal stress associated to the current flow may be obtained by calculating the per unit power dissipated by the cable's phases and shields subjected to the fault current flow.

- Phases: $P_{Jphase} = R_{ph}(I_{fTOT})^2$
  As known, in the cable's phases flows the sum of both the components I_{f1} and I_{f2}
- Shields: $P_{JSH} = R_{sh}\ I_f^2$
  As stated above in the cable's shield may flow the current component I_{f1} or I_{f2}, depending on the considered branch of the cable.

As mentioned before, the disconnection of the cable's shields reduces the fault current to the sole component I_{f1}. As it will further discussed later in this paper, the average reduction, in terms of dissipated power may reach a mitigation factor up to 67%.
This preliminary evaluation however, does not take into consideration the equivalent thermal inertia of the involved conductor.
In particular, since the shields are characterized by a small equivalent section, they are subjected to extreme thermal gradients due to the almost instantaneous temperature rise.

In order to evaluate the thermal rise of the impacted conductor, the Italian standard CEI 11-17 [4] has been used. In particular, assuming the fault current as a constant and considering the event as limited in time, the standard suggests the following relationship to calculate the through energy:

$$K^2 S^2 = I^2 t \qquad (3)$$

Where the parameter K can be calculated via:

$$K = \sqrt{\frac{\gamma_c(\frac{1}{\alpha} + 20)}{\rho_{20}} ln \frac{\frac{1}{\alpha} + \theta_{cc}}{\frac{1}{\alpha} + \theta_0}} \qquad (4)$$

By inverting the above equation is possible to calculate the final temperature reached by the conductor in the event of a fault:

$$\theta_{cc} = \frac{\theta_0 \alpha e^{\frac{\alpha I^2 \rho_{20} t}{(20\alpha+1)S^2\gamma_c}} + e^{\frac{\alpha I^2 \rho_{20} t}{(20\alpha+1)S^2\gamma_c}} - 1}{\alpha} \qquad (5)$$

Where the main parameters, according to the standard, represent:

- S: equivalent cross-section of the cable's phase or shield
- Θ_0 (phase): temperature of the phase, equal to 90°C as suggested by the standard
- Θ_0 (shield): temperature of the shields, equal to 60°C as suggested by the standard
- Θ_{cc}: maximum temperature reached (output of the algorithm)
- T: 0.49 s overall fault time as described above

THERMAL AGING

With regards the effect of these fault currents on the cable's insulation, different experimental aging models are available in literature [5], [6] and [7]. These models evaluate the expected lifetime of the insulation if operated at a specific temperature.
A first exponential model, based on experimental parameters [5]:

$$D(\theta_{cc}) = L_0 e^{-B(\frac{1}{\theta_{amb}} - \frac{1}{\theta_{cc}})} \qquad (6)$$

Where the coefficient L_0 and B are obtained experimentally:

Material	L_0	B
XLPE	9.350 * 10^8	12450
EPR	9.386 * 10^8	12430

Table 3 - Experimental coefficients of the model

A second, similar experimental model uses instead the following parameters [6]:

$$D(\theta_{cc}) = 10^{\frac{a+273a+b}{\theta_{cc}+273}} \qquad (7)$$

Where the coefficients a and b are assumed as follows:

Material	a	b
EPR	-11.627	6127

Table 4 - Experimental coefficients of the model

A third model, based on the interpolation of experimental values, directly links the reached temperature with the expected life of the cable [7]:

θ (°C)	D(θ) (hours)
250	2.8
230	6.9
210	35
190	120
170	640
150	1920
135	6700

Table 5 - Experimental tests regarding the expected life of the insulator

Using the above-mentioned aging models it was possible to evaluate the life reduction of all the 1780 fault events with each aging model, the average value was then considered as the output.

The aging models presented above do not correlate directly each fault to the life reduction of the cable, but represent the expected life of the insulation if operated at the Θ_{cc} temperature. In order to evaluate the reduction factor, the widely known Miner rule has been used:

$$\sum_{1}^{N} \frac{t_i}{t_{vi}} = 1 \qquad (8)$$

Where t_i represents the duration of the thermal stress (fault event) and t_{vi} represents instead the life expectancy at the

associated temperature.
To evaluate the associated life reduction, the relationship may be rearranged in order to make the expected life explicit:

$$\frac{t_{expected}}{t_{v90°C}} + \sum_{2}^{N} \frac{t_i}{t_{vi}} = 1 \qquad (9)$$

$$t_{expected} = \left(1 - \sum_{2}^{N} \frac{t_i}{t_{vi}}\right) \cdot t_{v90°C} \qquad (10)$$

The final equation then evaluates the expected life of the insulation subjected to multiple thermal stresses.

Using the above-mentioned approach the average life reduction of every considered fault event may be summarized in the following table:

Reduction per event (years/event)	Reduction per line (years/line)	% Reduction per event	% Reduction per line
-0,2267	-0,5935	-0,76%	-1,98%

Table 6 - Average life reduction of the insulation in the event of a CCF

As shown in the table above, the average life reduction of a cable, in the event of a cross-country fault, may be estimated in 0.76%, when considering an insulation life cycle of 30 years.
This analysis allowed evaluating also the average temperature rise during a CCF. The analysis showed that, keeping the cable's shield connected to the earth network, the average temperature of the phases, in direct contact with the inner insulation layer of the cable, reaches values up to 103°C, with a temperature rise of almost 13°C. On the other hand, the shield reaches an almost identical temperature value, but starting from an operating temperature of 60°C, with a thermal rise of 53°C, that affects the outer layer of insulation.
Repeating the same analysis assuming the cable's shields disconnected from the primary substation's earth network, an almost negligible temperature rise of the inner layer of insulation is reached. This supports the starting idea that the disconnection of the cable's shields reduces the thermal stress on the insulation, thus allowing a longer expected life.

STATISTICAL EVALUATION

In order to evaluate the benefits of the shields' disconnection technique, also by a statistical approach, the data regarding the CCF have been aggregated by the operating voltage level and then separated according to the shield's connection typology. This analysis, as summarized in the table 7, shows that the average number of CCF per line decreases significantly whenever the operation of the network infrastructure contemplates the cable's shield disconnected from the earth network in the HV/MV substation.

Voltage level	Average number of CCF per line (shield connected)	Average number of CCF per line (shield disconnected)	Reduction factor of CCF
<15 kV	0.125	0.0525	-0.0725
15 kV	0.185	0.155	-0.03
20 kV	0.2975	0.1825	-0.115

Table 7 - Average number of CCF aggregated for voltage level and shield's connection options

This reduction, as shown by the table above, may have also a significant impact on the quality of service indicators, in particular SAIDI and SAIFI.

CONCLUSIONS

In conclusion, this paper showed that the disconnection of the cable's shields at the primary substation end may reduce the thermal stress on the insulation, thus allowing an increased expected life of all the involved components. This approach was also validated by a statistical evaluation that underlined how the connection policy of the cable's shield already alter the average number of CCF in the e-distribuzione's network.

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