COMPARATIVE ANALYSIS OF GROUNDING SYSTEMS FORMED BY FEEDERS IN ONE CASE WITH UNINSULATED AND IN THE OTHER CASE WITH INSULATED METALLIC SHEATH

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ABSTRACT

It is well known that the metal-sheathed cables essentially affect the potentials appearing during a ground fault in substations located in typical urban surroundings. This fact was recognized early in the case of cables with uninsulated metallic sheath (the electrical protection). The metallic sheaths of these cables are in direct and continuous contact with earth, and in accordance with that these cables act as long grounding electrodes. As a consequence the underground cable lines belonging to the MV distribution network supplied by one HV/MV substation spontaneously form one very large grounding system around this substation. However, instead of this type of cable, constructed mainly as a three-core cable, cables with insulated metallic sheaths, constructed mainly as single-core cables are more and more applied in contemporary MV networks. The cables of this type do not act as grounding electrodes and the following quite logical question arise: how the cable of this type will affect the potentials appearing during a ground fault in different parts of such grounding system in dissipating the ground fault current into the surrounding earth (the so-called proximity effect) practically do not exist.

INTRODUCTION

Better exploitation characteristics, easier maintenance and more acceptable prices cause that the modern extruded dielectric cables, and especially cables with cross-linked polyethylene (XLPE) more and more replace the so-called conventional cables, i.e. paper-insulated cables. Bearing in mind this increasingly marked trend, it is not difficult to anticipate that in the foreseeable future mostly XLPE cables will be used in distribution networks. However, in meantime a question appeared how this change of the type of the utilized cables will reflect to the possibilities to successfully (i.e. safely and cost-effectively) solve the grounding problem of the distribution substations, especially those where this problem is the most marked, HV/MV substations.

It is well known that the construction of paper-insulated cables is such that their metal sheath is in direct and continuous contact with the ground. Thus under the conditions of a ground fault these cables act as long grounding electrodes, i.e. they inject the fault current directly into the ground. Owing to this, a very spacious and specific grounding system is formed in the wide area around the distribution HV/MV substations. The extremely advantageous characteristics of such grounding systems enable safe and cost-effective solution of the grounding problems (the safety conditions) even when the fault currents reach very high values of the order of 20 kA. Many theoretical and experimental investigations performed until now (e.g. [1]) show that the most part of the total fault current flowing to the ground (about 90%) is conducted through the metal sheath of these cables. What can be expected then if paper insulated cables are replaced with XLPE cables? It is known that these cables have an insulation layer over their metal sheath and thus do not act as grounding electrodes themselves. The posed question can be expressed in an even more direct way: will a widespread use of XLPE cables significantly impair the general conditions for the solution of the grounding problems of distribution substations? Since the answer to this question appears affirmative, many distribution companies adopted the procedure of laying copper wires (or galvanized steel strips) into the trench together with the cables with extruded dielectric insulation. The intention was obviously to compensate for the absence of the grounding function of the XLPE cables. However, further analyses showed that the effects of the use of such a "solution" are very limited and that the implementation of the "solution" itself results in unnecessary expenses.

This paper shows that the property which was until recently maintained to be a shortcoming actually represents an advantage of the XLPE-insulated cables. Actually, because of the improved electrical connection with the grounding systems of the neighboring substations, grounding systems with very advantageous characteristics are formed through the cables with extruded dielectric insulation. This conclusion obviously contradicts the previously stated widespread opinion (or maybe a better expression is prejudice) and, although it may sound paradoxical, its explanation is quite logical. Through the insulated metallic sheaths a significantly wider grounding system is formed than that through paper insulated cables. Because of that there is no unfavorable proximity effect among the nearby parts of the grounding system when dissipating the fault current into the ground. In the light of these facts, a question appears if it is justified to use so large cross sections of metallic sheaths as those currently used for the XLPE cables (Cu 16 mm² and Cu 25 mm²) in the MV networks. In this respect this paper is a continuation of the investigation presented in [7].

This paper gives a detailed analysis of the grounding effects of paper insulated cables and cables with extruded dielectric insulation, including their mutual comparison. The results of the analysis show that the conditions for the solution of the grounding problems of the distribution HV/MV stations are...
very favorable even if XLPE cables are used in MV networks. When the grounding conditions of the substations in MV networks are regarded, a care must be also taken about the influence of the used type of cables to the distribution of the ground fault current. Since the value of the reduction factor in the cable lines with XLPE cables is less favorable (the reduction factor \( r \) is about 0.5) than that in paper insulated cables \( (r = 0.2) \) it can be said that the overall influence of these cables to the grounding conditions of MV/LV stations is significantly less favorable. However, in typical urban environment a large number of mutually connected (through the LV neutrals) metallic structures exist in the earth independently of our need to solve the grounding problems (the reinforcement of concrete building foundations, different type of steel pipelines, etc.). In general case, their influence on the grounding problem of MV/LV substations is so favorable that this advantage of the paper cables is not indispensable, and actually it does not have any practical importance.

**DESCRIPTION OF THE GROUNDING SYSTEM TO BE CONSIDERED**

The analysis presented in this paper was performed on an practical example of a 110/10 kV station in the distribution network of Belgrade. It is a gas-insulated substation in a surrounding that may be considered as typical for urban conditions. To obtain a more complete insight into the spatial disposition of the main elements of the grounding system we use the simplified schematic presentation in Fig. 1.

\[
\begin{array}{c}
\text{S} \quad \text{110/10 kV station} \\
1, 2 \text{ and } n - \text{directions of cable laying} \\
\text{n} \in [1, 4]
\end{array}
\]

**Fig. 1 Characteristic disposition of cables belonging to a given (n-th) primary direction of laying**

The main parts of the grounding system in the case under consideration consists are the foundation of the building where the station is located and the uninsulated metallic sheaths of the cable lines going out of the station building. The foundation of the building covers an area with the dimensions 26 m and 52 m. The relevant data about the surrounding 10 kV cable network are as follows:

- There were \( N_c = 11 \) outgoing cable lines in the moment of putting the substation in operation (which is a critical moment regarding the number of the connected cables). We can represent their spatial disposition by using diagram in Fig. 1 (the general case). In three substantially different (primary \([1]\)) directions the groups of three cables each were laid down, as in Fig. 1, while in the fourth two cables were laid, one of them in the primary, and the other in the secondary direction \([1]\).
- The points of separation of particular cables (points 1 and 2 in Fig. 1) from the joint trench (secondary directions of laying \([1]\)) for the particular primary directions are at the following distances from the station building: 210 m and 320 m; 300 m and 390 m; 220 m and 290 m; and 420 m.
- All cables are with non-insulated metallic sheaths with an external diameter of 44 mm and are buried in the ground at a depth of 0.7 m.
- The longitudinal self-impedance of the metallic sheath of the cables is (0.0007 + j0.002) \( \Omega/km \);
- Each of the cable lines is 3 km long in total and each supplies nine TC10/0.4 kV located at an average mutual distance of about 300 m; the average grounding resistance (impedance) is about 0.5 \( \Omega \) (the grounding effects of the connected cables are not taken into account).

The whole grounding system is situated in the ground with an equivalent resistivity estimated to about 30 \( \Omega.m \).

**CALCULATION RESULTS AND THE COMMENTS TO OBTAINED RESULTS**

Based on the previously presented data, a calculation has been performed utilizing the method described in \([1]\). The method takes into account all relevant factors with the only exception of the grounding electrodes of the supplied 10/0.4 kV stations. In this manner an error is introduced into the calculation that is slightly on the safe side. It should be mentioned here that the number 2 is erroneously included in expression (6) in \([1]\).

The calculation furnishes the following results:

- The active cable length, i.e. the length on which the cable performs its grounding function is approximately 450 m.
- The grounding impedance at the beginning of each of the connected cable lines, if considered separately from the other parts of the grounding system, is

\[
(0.335 + j 0.238) \ \Omega.
\]

- The equivalent grounding impedance of all of the connected cable lines considered within the whole structure of the grounding system is

\[
Z_e = (0.033 + j 0.051) \ \Omega, \quad \text{or} \quad |Z_e| = 0.061 \ \Omega.
\]

The impedance \( Z_e \) is determined taking into account the proximity effect \([2]\), i.e. the mutual interference in dissipating the current into the earth between the station grounding electrode (the station building foundation) and the cables.
acting as grounding electrodes, as well among the cables as grounding electrodes themselves.

If for the sake of this analysis we start from the unrealistic assumption that there is no proximity effect, then the grounding contribution of the cable lines becomes much larger. The equivalent grounding impedance of all of the connected cable lines is in that case

\[
Z' = Z_{\infty} = \frac{0.335 + j0.238}{11} = (0.032 + j0.022) \Omega
\]

or

\[
|Z'| = 0.039 \Omega
\]

It can be seen that the mutual interference in injecting the fault current into the earth between the station grounding electrode and the cable lines, as well as that among the cable lines, makes that the equivalent grounding impedances representing the grounding contribution of all cable lines in the concrete case increases by 0.022 \( \Omega \), or expressed in relative units the enlargement is 57%.

The question to be answered is the following. What would happen if the 10 kV cable lines connected to the considered 110/10 kV station were built with XLPE cables instead of paper insulated cables?

GROUNDING SYSTEM FORMED THROUGH XLPE CABLES

First we consider only a single 10 kV cable line, which supplies the 10/0.4 kV substations in a series, whose a total number is \((N-1)\) in the general case. Introducing certain idealizations of the real electric circuit formed by the metallic sheaths of 3 single-core cables and the grounding electrodes of the supplied substations, such a cable line can be represented by the equivalent circuit shown in Fig. 2.

![Fig. 2. Equivalent circuit of a cable line.](image)

The notation used in the presented circuit is as follows:

- \( Z_C \) equivalent grounding impedance of a cable line, as seen from the supplying station,
- \( Z_{SH} \) self-impedance of 3 parallel metallic sheaths on the section of the cable line with a length equal to the average length of all its sections, where one section is defined as a cable length between two nearby substations,
- \( Z_{R} \) (\( R \)) average value of grounding impedance (resistance) of supplied substations,
- \( Z_b \) grounding impedance of the supplying station at the opposite end of the cable line.

Since the circuit shown in Fig. 2 obviously represents an uniform discrete parameters ladder circuit, the equations derived in [3] are valid for it. Using these equations with simultaneously neglecting the grounding impedance at the opposite end of the line \((Z_b=0)\) it can be shown that the impedance \( Z_C \) is determined by the following relation:

\[
Z_C(Z_b \approx 0) = \frac{k^{2N-1}}{k^{2N} + k} Z_{\infty}
\]

(1)

In the given expression \( k \) represents the coefficient of current distribution in the circuit nodes \( 1, 2, 3, ..., N \) under the assumption that the number of the nodes is infinite \((N \rightarrow \infty)\). It is determined by the following relation

\[
k = 1 + \frac{Z_{sh}}{Z_t}
\]

(2)

where the impedance \( Z_t \) represents the input impedance of the circuit with an infinite number of nodes \((N \rightarrow \infty)\). This impedance is determined as

\[
Z_{\infty} = \frac{Z_{sh}}{2} + \sqrt{Z_t Z_{sh} + \frac{Z_{sh}^2}{4}}
\]

(3)

When the cable lines are long enough, i.e. when if they are longer than their active length (the length beyond which the increase of the line length does not have an influence to the value of the grounding impedance \( Z_C \)) instead of (1) the simpler equation (3) can be used. According to the analogy between the electrical circuit in Fig. 2 and the circuits formed by the grounding wire(s) and the footing of the towers of the overhead line [4] the active length of the cable line can be estimated using the expression

\[
N_a = \left\lfloor \ln \left( \frac{1 + \frac{1}{\varepsilon}}{1 + \frac{|Z_{sh}|}{|Z_t|}} \right) \right\rfloor
\]

(4)

Where

- \( N_a \) the active length of the cable line given as the number of the cable sections, observed from the supplying TS and
- \( \varepsilon \) desired relative accuracy, \( |Z_C - Z_{\infty}| / Z_{\infty} \) equals 0.05
In typical urban conditions the total length of the feeding cable lines in a 10 kV network is approximately 3 km, so that according to (4) and the really possible values of the impedance \( Z_e \) in many practical situations we can treat each of them as infinitely long from the standpoint of the grounding effects.

The parts of the grounding system mutually connected by metallic sheaths of the feeding cable line (i.e. the grounding electrodes of the supplied 10/0.4 kV substations) are at such distances (usually several hundreds of meters) that mutual interference between them in performing the functions of the grounding electrode practically does not exist. This is also valid for the substations supplied by different cable lines, so that the grounding impedances of all connected cable lines is determined by the simple relation

\[
Z_e = \left( \frac{N_c \sum_{l=1}^{N_c} l Z_{sh}}{N_C} \right)^{-1}
\]

or, in a special case when the parameters \( Z_e \) and \( Z_{sh} \) of all connected cable lines are approximately equal,

\[
Z_e \approx \frac{Z_{sh}}{N_C}
\]

To use these expressions, we also need the values of the impedances \( Z_e \) and \( Z_{sh} \). The impedance \( Z_{sh} \) is calculated according to the data on the number and the cross-section of the metallic sheaths of one line, the average length of the cable sections and the equivalent resistivity of the soil where the line cable is laid. At that, analytical expressions are used which are derived according to the Carson's theory of the feedback of the fault current through the ground (e.g. [5]).

For the sake of this analysis we adopt that the metal sheath is in one case Cu 25 mm², and in the other case Cu 10 mm². In the second case we chose the smallest standard cross-section of metallic sheath in XLPE cables able to withstand without damages the thermal stress under the conditions of ground fault in a 10 kV network (ground fault current limited on the value of 300 A).

By previously adopting a relatively low value of the impedance \( Z_e \) (0.5 \( \Omega \)) we bore in mind that the 10/0.4 kV substations use a single grounding electrode connected via neutral conductors of the low voltage (0.4 kV) network with different metal constructions (different type of steel pipelines, building foundations, etc.) which independently of their primary function also act as grounding electrodes.

According to the analytical expressions presented here and the adopted relevant data we performed the necessary calculations, obtaining the following values

- The case Cu 25 mm²
  \[ Z_e = (0.028+j0.034) \Omega, \text{ or } |Z_e| = 0.044 \Omega \]

- The case Cu 10 mm²
  \[ Z_e = (0.043+j0.030) \Omega, \text{ or } |Z_e| = 0.052 \Omega \]

It can be seen that the calculated values for the impedance \( Z_e \) are even a little smaller than the value obtained for the case of the paper insulated cables \( (Z_{sh}=0.061 \Omega) \). A logical question stems from here. What explains these so favorable grounding effects if we bear in mind that the XLPE cables do not function as grounding electrodes, i.e. they do not inject the fault current directly into the ground?

### COMPARATIVE ANALYSIS OF THE GROUNDING EFFECTS OF DIFFERENT CABLE TYPES

First of all, the metal sheaths of the XLPE cables function as electrical lines (insulated conductors) through which, because of their large axial conductance, i.e. a better transfer of the fault current, a much wider grounding system is formed than in the previous case. Using expression (4) one can estimate the area covered by such a grounding system for a 110/10 kV station. It is an area defined by a radius of approximately 1640 m (Cu 25 mm²), or 1460 m (Cu 10 mm²) around the substation, and thus it is about thirteen times (Cu 25 mm²), or about ten times (Cu 10 mm²) larger than in the previously considered case. This fact is the reason for the more intensive transfer of the fault current to the distant parts of the grounding system of the 110/10 kV station formed through the metallic sheaths of this type of cables. At that, another important fact is that between the parts of the grounding systems formed by this type of cables mutual interference (proximity effect) in dissipating the fault current into the ground practically does not exist. All these facts represent the reasons for the exceptionally favorable grounding effects of the cable lines with XLPE cables.

The performed analysis represents a sufficient basis for another important observation. There are no reasons to fear that a wide use of XLPE cables with a reduced cross-section of its metallic sheath (Cu 10 mm²) could challenge the possibility to achieve the safety conditions in the future HV/MV kV stations. The slightly more favorable grounding effects of the metallic sheath, Cu 25 mm², can be compensated, if a need for this occurs at all, by additionally connecting only one or two of outgoing cable lines. They will be anyway connected otherwise, but at some later time. As an illustration the final number of the connected cable lines in the considered station is 44.

In order not to remain with a single example, we will consider the cases where the conditions are identical to the considered 110/10 kV station, but the soil resistivity is increased. These cases can be foreseen on the basis of the fact that long
grounding conductors are specific in that they partially compensate the unfavorable influence of the increase of soil resistivity [6]. This favorable effect in the case of the grounding systems formed with the XLPE cables is more pronounced because of the fact that the proximity effect in emanating the fault current into the surrounding ground in that case practically does not exist [6]. This means that for some increasingly larger values of soil resistivity the characteristics of a grounding system with XLPE cables will become more and more favorable in comparison to those of a grounding system under the same conditions, but utilizing the paper insulated cables.

The presented procedure of calculating the grounding effects of the cable lines can be also used for the calculation of the equivalent grounding impedance of the MV/LV substations. The only difference is in the fact that in that case the connected cable line lengths depend on the position of a certain MV/LV substation along the feeding cable line and vary from one to (N–1)-th cable line sections (Fig.2). Thus, in many practical situations the expression (1) is more accurate than expression (3).

CONCLUSIONS

The analysis performed in this paper shows that an increasing use of the XLPE cables in the MV networks will not significantly change the general conditions for solving the grounding problems of the distribution substations. In other words, the use of this type of MV cables will not put in question the modern concept of solving the grounding problems in distribution substations, based mostly on the grounding effects of the cable lines in MV distribution networks.

The production and the utilization of XLPE cables with the metallic sheaths Cu 10 mm² instead of the current Cu 25 mm² or Cu 16 mm² enables significant financial savings, and the possibilities for an efficient and cost-effective solution of the problem of the grounding of distribution HV/MV and MV/LV substations still remain very favorable.

REFERENCES


