

Compact Model of a Combined Overhead-Cable Line for Ground Fault Application Transfer Analysis

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Abstract: - When a fault to ground occurs at a substation supplied by a combined overhead-cable transmission line, a significant portion of the fault current flows through the grounded cable sheaths and discharges into the earth at the transition station, where cables are connected to the overhead line. This phenomenon, named “fault application transfer”, may result in high ground potentials at the transition station which may cause shocks and equipment damage. This paper presents a simple but accurate circuit model of both the overhead and cable line sections, that allows the computation of the fault current transferred at the transition station using simple equations derived from the application of Kirchhoff's laws. Numerical analysis shows that, in practical cases, more than 25% of the fault current could involve the transition station due to fault application transfer. In this situation the local ground electrode, typically of high ground resistance with a small grid, could be inadequate maintaining the ground potential rise within safety limits.

Key-Words: - Grounding systems, fault current distribution, overhead ground wire, cable sheaths.

1 Introduction

The main task of a substation grounding system is to discharge into the soil the maximum ground fault current expected, without exceeding safety limits for touch and step voltages within the substation and the surrounding area. Despite the usually high value of the fault current and other unfavorable conditions (high soil resistivity, restricted area for laying the earth electrode, high back-up protection time), this task is often greatly facilitated by the presence of various different metallic return paths which allow a substantial reduction of the fault current discharged by the substation grounding grid. Through such conducting paths connected to the grid (i.e. overhead ground wires, cable sheaths, feeder neutrals, auxiliary earth conductors, etc.), a consistent part of the fault current flows toward the remote source either directly or through other auxiliary ground electrodes. Where this situations exists, these ground return paths should be taken into consideration in the design of the substation ground grid [1].

In practice, a large portion of the fault current is diverted away by ground return paths associated to the feeding transmission lines, mutually coupled with the faulted phase conductor, while a smaller quantity is carried by neutrals or return paths of outgoing lines providing a ground impedance in parallel with the substation grid [2, 3, 4]. In particular, if the substation is fed by a cable transmission line, a very large percentage of the fault current (up to 95% for cable line consisting of three single core cables) will returns via

the cable sheaths due to their strong inductive coupling with the phase conductors [5].

Nevertheless in this way, although the ground potentials at the faulted substation can be maintained within acceptable levels by a cost-effective yet still safe ground system, hazardous potentials may appear at some other remote installations, i.e. where the current diverted by the metallic return paths is discharged into the soil through their intermediate ground connections. A typical example is represented by the overhead line towers, especially those nearest to the fault, where a significant part of the return current through the ground wire is released into the soil through their ground electrodes. Many authors in the past have presented various analytical methods to evaluate accurately the fault current distribution between substation grid, ground wires and towers; different mitigation methods have been suggested to prevent hazards to humans: a comprehensive list of related references is given in [1].

A more critical situation not yet extensively dealt with in literature occurs when a substation is fed by a combined overhead-cable transmission line. In these cases, due to the difference in coupling factors for cable and overhead lines, a consistent part of the ground fault current flowing through the cables sheath is injected into the soil at the point of discontinuity (transition station) where the cables are connected to the overhead line; from there the return current continues toward the remote source through the earth, rather than through the overhead ground wire. This may result in high ground

potentials at the transition station, causing shocks and equipment damage, as mentioned by Sobral et al. [6] referring to a practical case. This phenomenon, presented for the first time in literature and called "fault application transfer" by the authors, has no relation with the well-known potential transfer effect. An overhead-to-underground transition station occupies a very small area compared to a conventional substation and in some case it consists simply of a dead-end steel pole structure (transition pole), so that its ground electrode, small and of high resistance, is inadequate to maintain the ground potential rise within safety limits in case of a fault application transfer. The results of a measurement campaign of the ground fault current distribution during a fault at a HV/MV substation fed by a multi combined overhead-cable transmission line are reported in [7]. As expected, measurements have shown that more than 25% of the fault current flows between each transition station's ground electrode and the surrounding earth, causing dangerous voltages exceeding allowable safety limits. Moreover, it has been shown that ground fault transfer effects involves all the transition stations of the feeding line, almost in the same manner, even if they are located far away from the faulted substation.

Overhead to underground cable transition can occur at a nearby transformer substation (transit substation) whose incoming circuit is aerial. In this case the current due to a ground fault transfer does not give rise to any additional safety concerns at the transit substation, if its grounding system is properly designed for the local ground fault current. The effects of fault application transfer have been utilized in [8] in designing the substation ground grid in a dense urban area, to provide a suitable technical control of potential rise in order to ensure safety conditions and avoid difficulty in soil resistivity and ground grid resistance measurements. Two additional bare copper bondings, tied to the cable sheaths, have been also considered in the final design to better achieve the predetermined objective.

From the above considerations it is clear that fault application transfer effects must be properly taken into account at the design stage of substations fed by a combined overhead-cable line, both for a more efficient and economic grounding system design as well as for safety concerns at the transition stations. Some authors have yet presented different methods for evaluating ground fault current distribution in station supplied by non uniform lines and lines combined with cables [9, 10]. Nevertheless, these methods and their applications are focused only on evaluating the earth current and voltages at the faulted station and not at the transition station.

In this paper a simple but accurate method is presented for computing both the earth current at the faulted station as well as the fault current transferred at a transition station and their ground potentials rise, during

a ground fault at a remote substation fed by a combined overhead-cable line. The method utilizes compact equivalent models of both overhead and cable line sections and uses simple equations derived from the application of Kirchhoff's laws. The circuit models are built taking into account all the relevant parameters and the total ground fault current at the remote substation is assumed as known from system studies. For the first time a numerical analysis of the fault application transfer effect is also performed, the goal of which is to estimate the entity of this phenomenon by referring to practical cases.

2 Problem Formulation

Consider a substation fed by a combined overhead-cable transmission line with the shield wire and cable sheaths grounded at both ends of each section, as in Fig. 1. In the case of a phase-to-ground fault at the substation, the triple zero-sequence current $3I_0$ flowing through the phase conductors is in part injected into the soil through the local ground grid (I_E); in part it returns to the remote sources through the cable sheaths and the overhead shield wire, as the result of both galvanic connection and inductive coupling with the faulted conductor.

Nevertheless, due to the difference in coupling factors for cable and overhead lines, part of the fault current flowing through the cable sheaths is injected into the soil at the transition structure, continuing toward the remote source through the earth rather than through the overhead shield wire.

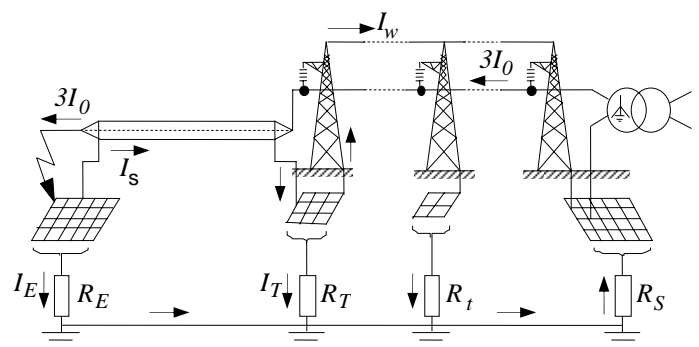


Fig. 1 - Ground fault at a substation fed by a combined overhead-cable line.

At the design stage, the knowledge of the proper earth currents I_E at the faulted substation is the basis to make a safe and economically convenient grounding system. Moreover, it is of prime importance also to evaluate the amount of the fault current transferred to the transition structure I_T , in order to make sure that dangerous local voltages do not exceed safety limits, thus preventing shock hazards due to fault application transfer effects.

With reference to the notation used in Fig. 1 the following relations hold:

$$I_E = 3I_0 - I_s \quad (1)$$

$$I_T = I_s - I_w = 3I_0 - I_E - I_w \quad (2)$$

where I_s is the total return current flowing through the sheaths of the three single core cables and I_w is the portion of the return current carried through the overhead shield wire at the transition structure.

Apart from the characteristics of the overhead shield wire (number, material, size, spacing from phase conductors), I_w depends also on the grounding resistance of the line towers, whose value is not constant along the line but varies with the soil resistivity of the sites where the towers are located. However, it is a common practice at the design stage to adopt an approximate value, corresponding to the estimated average value.

3 Circuit Models

3.1 Overhead line

During a fault to ground, the overhead feeding line can be represented by the compact equivalent diagram in Fig. 2, by using the decoupling technique [11, 12].

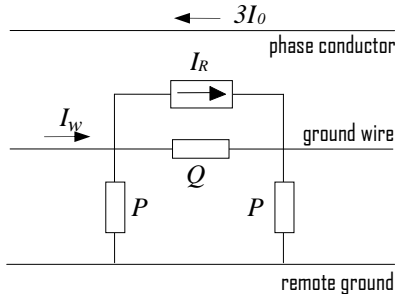


Fig. 2 – Compact equivalent diagram of an overhead line during a fault to ground.

The current source

$$I_R = 3I_0 \frac{Z_{cw}}{Z_w} \quad (3)$$

models the fault current component flowing through the shield wire due to its inductive coupling with the phase conductors, where Z_{cw} represents the mutual impedances of the overhead ground wire and the phase conductors and Z_w the self-impedance of the overhead ground wire. Both impedances are per span and for earth return and can be evaluated by means of Carson's theory [13], once the soil resistivity and the characteristics of the shield wire (number, material, size, spacing from phase conductors, etc...) are

assigned. The equivalent π -circuit models the shield wire self-impedances and the tower footing resistances of the N spans of the line; its parameters are determined by the following expressions [14]:

$$P = \frac{k^{2N} - 1}{k^N + k^{N+1}} Z_\infty \quad (4)$$

$$Q = \frac{k^N + 1}{k^N + k} Z_\infty \quad (5)$$

where:

$$k = 1 + \frac{Z_\infty}{R_t} \quad (6)$$

In the above equations Z_∞ represents the equivalent impedance of the ground wire and its connections to earth, through the transmission towers, of an infinite line length. Its equation is [11]:

$$Z_\infty = \frac{Z_w}{2} + \sqrt{R_t Z_w + \frac{Z_w^2}{4}} \quad (7)$$

where R_t is the tower footing resistance.

3.2 Cable line

In the case of a phase-to-ground fault fed by a cable line consisting of three coated single-core cables with metallic sheaths, the equivalent diagram is that in Fig 3.

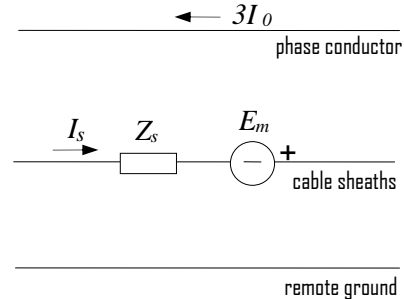


Fig. 3 – Compact equivalent diagram of a cable line during a fault to ground.

In this case, the voltage source

$$E_m = 3I_0 Z_{cs} \quad (8)$$

models the emf's induced by the phase conductors (each of them interested by the zero-sequence current I_0) upon the cable sheaths, due to their inductive coupling; where Z_{cs} represents the mutual impedances of the cable sheaths with the phase conductors. Z_s is the self-impedance of the cable sheaths, all operating in parallel, with common earth return.

Both impedances can be evaluated by means of Carson's theory, once the soil resistivity and the characteristics of the cable sheaths (material, size,

spacing between phase conductors, etc...) are assigned. It is assumed that the return current I_s divides equally between the three sheath circuits; this is undoubtedly truth with the cables in trefoil formation, but it can be assumed to be so also when the cables are laid flat with little error [15].

3.3 Combined overhead-cable line

Combining the diagrams of Fig. 2 and 3 and including the resistance to ground of the grounding systems at the ends of each line section, the equivalent circuit of Fig. 4 is obtained for a combined overhead-cable line during a fault to ground at the supplied substation.

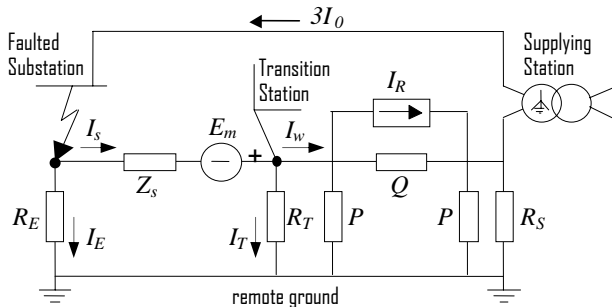


Fig. 4 - Equivalent diagram of a combined overhead-cable line feeding a fault-to-ground at a substation.

The ground currents at both the faulted substation and the transition station can be obtained by solving, with respect to I_E and I_T , the system of linear equations derived by applying Kirchhoff's voltage and current laws to the circuit in Fig. 4.

The ground potential rise at the transition station can then be obtained as:

$$U_T = I_T R_T \quad (9)$$

The equivalent diagram in Fig. 4 allows some interesting remarks. For a given length of the cable line section the value of Z_{cs} is almost equal to Z_s , so that according to (1) and (8):

$$E_m = 3I_0 Z_{cs} > I_s Z_s = (3I_0 - I_E) Z_s \quad (10)$$

This means that the effect of the inductive coupling on the return current through the cable sheaths prevails over the voltage drop produced by the return current itself along the cable sheaths. By increasing the cable length, the voltage source E_m increases more than the voltage drop along Z_s , forcing most of the fault current toward the cable sheaths. In other words, the longer the cable line, the greater the fault current diverted from the substation grid. For a given length of the overhead line section the value of Z_{cw} is much lower than Z_w , resulting in a value around $Z_{cw}/Z_w = 0.1$.

The component of I_w due to the inductive coupling between the shield wire and phase conductors (I_R) is then very small. Moreover, the value of the impedance Q of the π -circuit is much greater than P . Consequently, the conductive component of I_w is only that due to the ground connections of few spans of the shield wire and, in accordance with (4) and (7), it is dictated by the self-impedance of the shield wire and by the tower footing resistance.

From this derives the fact that a consistent part of the return current flowing through the metallic sheaths of the cable line section may be expected to be dissipated into the earth at the transition station, as a consequence of the "bottle neck" created by the shield wire of the overhead line section.

4 Numerical Analysis

Consider a 110 kV combined overhead-cable transmission line supplying a substation, as schematically depicted in Fig. 1. The overhead line has a 50 mm² steel shield wire with a geometric mean distance (GMD) with phase conductors of 8,21 m; the average span length is 200 m, while the towers' footing resistance is 10 Ω .

The underground cable section consists of a trefoil formation of coated single-core cables having the following characteristics: 50 mm² copper sheath, geometric mean radius of the sheath 0.0434 m, GMD between phase conductors 0.25 m.

The overhead line section is considered infinitely long; in practice, this means that its effect on fault current distribution does not change with lengths of more than 15-20 spans. For this study, the length of the simulated overhead line is 10 km.

The other relevant data are:

- specific soil resistance: 50 Ω m;
- source ground impedance: $R_S = 0,5 \Omega$;
- substation grid impedance: $R_E = 0,1 \Omega$.

The curves illustrated in Figs. 5 and 6 yield the substation grid current and the current dissipating from the TS ground electrode, respectively, as a function of the cable line length (L), for different values of the TS ground resistance. The currents are per-unit absolute values. It can be observed that the distribution of the fault current between the grid substation and the TS electrode is dramatically affected by the length of the cable line section. For example, assuming $R_T = 2 \Omega$, when $L = 1$ km the percentage of the fault current dissipating from the substation grid is 79% and from the TS electrode is 19%, while when $L = 10$ km they are 37% and 46%, respectively.

The TS ground resistance influences the current dissipating from the TS ground electrode more than the substation grid current.

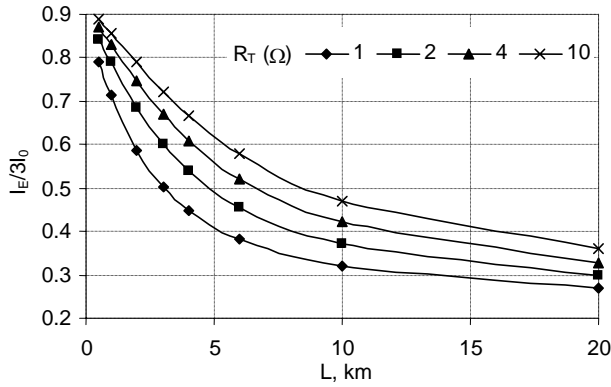


Fig. 5 – Substation grid current against cable line length.

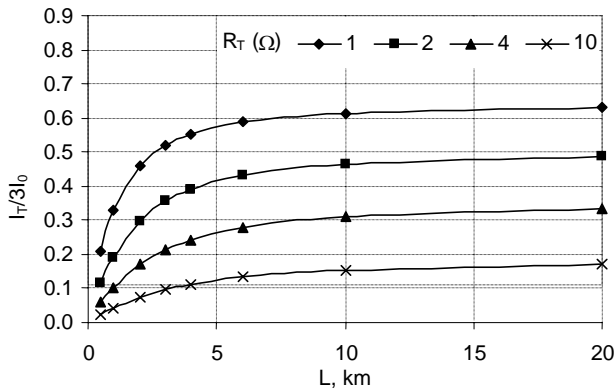


Fig. 6 – Current dissipating at the TS against cable line length.

The higher the TS ground resistance, the lower the return current is injected at the TS. Nevertheless, high value of R_T does not imply better safety conditions at the transition station, in terms of ground potentials. This is shown in Fig. 7, where the TS ground potential rise (GPR) given by (9) is reported, in per-unit and for different values of R_T .

Note that in the case of a high value of R_T (for example 10 Ω , the value assumed for tower footing resistance) the return current through the cable sheaths could be high in any case, as can be seen from the relatively low values of I_E up to a certain L (Fig. 5). This means that a relevant part of the return current will be shared between the overhead line towers. With reference to the diagram in Fig. 4, this means also that by increasing R_T the current I_T decreases while I_w increases.

The most critical towers are obviously those nearest the TS, since they offer a lower impedance path to I_w . In this case, a detailed study with a proper methodology and adequate software tools is required [16], to evaluate the current injected at the critical towers. As an example, Table 1 shows the current discharged at the first two towers, starting from the TS, for different values of R_T when $L = 10$ km; for comparison the current at the TS is also reported.

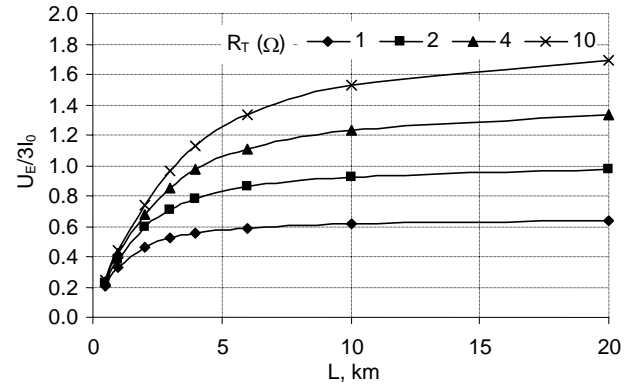


Fig. 7 – GPR at the transition station against cable line length.

Table 1 – Return current distribution between the TS and the first two towers, for different values of R_T and $L = 10$ km.

R_T, Ω	$I_T/3I_0$	$I_{T1}/3I_0$	$I_{T2}/3I_0$
0.5	0.730	0.029	0.023
1	0.614	0.049	0.039
2	0.463	0.074	0.059
4	0.309	0.098	0.078
10	0.153	0.122	0.097

4 Conclusion

In this paper a simple but accurate circuit model of a combined overhead-cable line has been presented. The model easily allows the computation of the fault current distribution between the grounding grid of the substation where the fault occurs and the electrode of the transition station of the overhead-cable line, as a result of fault application transfer.

Numerical analysis shows that, in practical cases, up to 25% of the fault current that appears at a remote substation could involve the transition station. In this situation the local ground electrode, generally of high ground resistance with a small grid, could be inadequate to maintain the ground potential rise within safety limits. In the case of a high ground resistance value for the transition station electrode, a relevant part of the return current will be shared between the overhead line towers. A detailed study is required in this case, in order to evaluate the current injected at critical towers and to establish safety conditions.

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