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A Method of Prelocalization Improvement of Resistive Faults Affecting Long Single-phase Underground Cables: Analytical and Numerical Calculation

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Abstract. *To ensure the continuity of the energy supply, we have to locate precisely the electrical fault affecting the underground cables and to repair them quickly. The exact localization of the fault is based on the prelocalisation method. In this paper, firstly a model of a single phase underground shielded high-voltage cable based on the distributed parameters approach is presented. Secondly, an algorithm of fault prelocalization implemented with the Matlab software is given. The fault distance and resistances are numerically and analytically computed by combining the electrical system behavior, before and during the incident. Only voltage and current measurements available in voltage source substation are used. Scenarios of frank and resistive fault types are applied to the 150 kV underground cable, connecting high voltage sub-stations of Tyna - Taparoura - Sidimansour in Sfax city - Tunisia. As the fault distance error rise with the cable length because of the capacitive current, we have the idea to introduce a compensate inductance in the earthing system. Finally a validation study is approved by the software Simulink-SimPowerSystems of Matlab showing the robustness of the developed prelocalization improvement approach according to the insulation fault nature and the fault place variation.*

1. Introduction

The urban zones development and environmental considerations have supported the use of underground power cables instead of overhead lines. Underground cables have many advantages compared to overhead lines. In fact, they practically do not require maintenance and especially are not affected by the unfavorable climatic conditions. However, when fault happens, the restore time is relatively long due to the various

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stages of fault identification, classification and location estimation in differed time [1,2]. Then to guarantee the electric power continuity, the electricity companies need to identify and locate rapidly and precisely the faulty segment in order to reduce the interruption duration [2, 3]. This objective can be reached only by the implementation of simple, rapid and accurate techniques of fault prelocalization.

The main paper aim is to develop a method, by introducing a compensation inductance in the earthing system, to ameliorate the fault distance precision in the resistive fault cases affecting the long single phase underground cables. This study is made in collaboration with the Tunisian Company of Electricity and Gas (STEG) by the application of the developed approach to the single phase underground cable connecting high voltage substations of Tyna, Taparoura and Sidimansour in Sfax city - Tunisia.

The cable modeling is based on the distributed parameters theory [4-8]. The fault equations resolution requires the knowledge of the boundary conditions. These are calculated from the voltage and current recordings available at voltage source substation and the electrical network configuration. Several simulation scenarios using the developed approach are presented and compared with the obtained results with the software SimPowerSystems of Matlab.

2. Cable modeling

The selected cable is a shielded single-core underground 150 kV type which a general description is given in [9]. In our case, the earth connection system, presented in figure 1, is the solid bonding [10, 11, 12] where the sheath is connected to the ground at the two cable ends through identical impedances $Z_n = R_n + jL_n\omega$. L_n indicates the compensation inductance. The distributed parameters theory is used to model the cable. An elementary length of cable is model by three distributed model conductors presenting core, sheath and ground (figure 2).

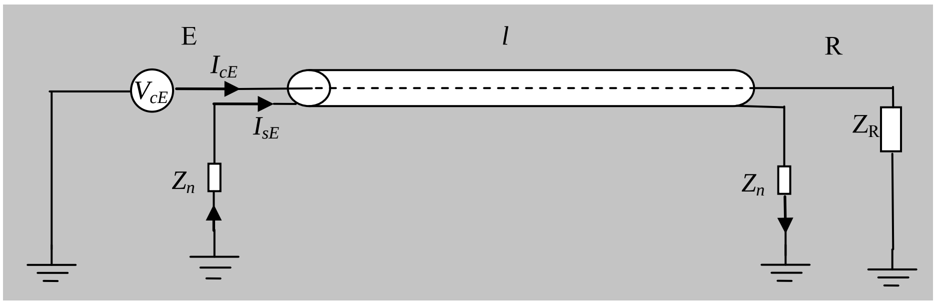

Fig. 1. Earth connection system of the cable

Each conductor is modeled longitudinally by an impedance per unit length $Z_i = R_i + jL_i\omega$ and transversely by an admittance per unit length $Y_{ij} = G_{ij} + jC_{ij}\omega$. R_i

and L_i represent respectively the resistance and the inductance of the conductor whereas w (rd/s) indicates the angular frequency. The conductance G_{ij} and the capacitance C_{ij} depend on the insulators nature between core and sheath (RP) and between ground and sheath (EP) [13, 14]. Subscripts i and j refer to core(c), sheath(s) and ground (g).

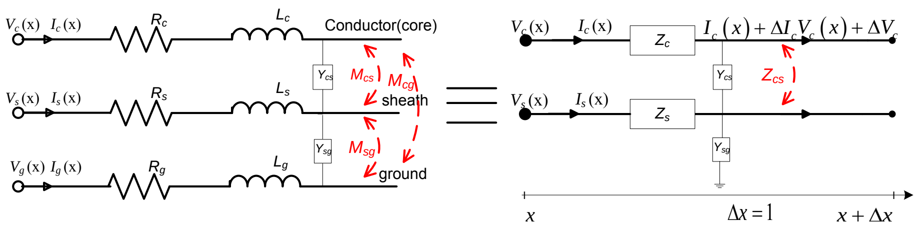

Fig.2. Distributed parameters cable model

Voltages (V) and currents (I) depend on time t and distance x counted positively from the sending-end (E) to the receiving-end (R). In permanent sinusoidal mode and by applying the Kirchhoff laws to the suggested elementary model the expressions of the voltage and the current variations in the core and the sheath are given in the matrix form as (1) [4, 5, 8, 13].

$$-\begin{bmatrix} \frac{\partial V}{\partial x} \\ \frac{\partial I}{\partial x} \end{bmatrix} = \begin{bmatrix} 0 & Z \\ Y & 0 \end{bmatrix} \times \begin{bmatrix} V \\ I \end{bmatrix} \quad (1)$$

The expressions of V, I, Z and Y are given in details in [4, 5, 9].
After some equations manipulation given in details in [4, 5], we deduce in (2) the final model of our cable in its hyperbolic form.

$$\begin{aligned} V_c(x) &= C_1 \cosh(\lambda_1 x) + C_2 \sinh(\lambda_1 x) + C_3 \cosh(\lambda_2 x) + C_4 \sinh(\lambda_2 x) \\ V_s(x) &= C_1 \alpha_1 \cosh(\lambda_1 x) + C_2 \alpha_1 \sinh(\lambda_1 x) + C_3 \alpha_2 \cosh(\lambda_2 x) + C_4 \alpha_2 \sinh(\lambda_2 x) \\ I_c(x) &= C_1 \alpha_3 \sinh(\lambda_1 x) + C_2 \alpha_3 \cosh(\lambda_1 x) + C_3 \alpha_4 \sinh(\lambda_2 x) + C_4 \alpha_4 \cosh(\lambda_2 x) \\ I_s(x) &= C_1 \alpha_5 \sinh(\lambda_1 x) + C_2 \alpha_5 \cosh(\lambda_1 x) + C_3 \alpha_6 \sinh(\lambda_2 x) + C_4 \alpha_6 \cosh(\lambda_2 x) \end{aligned} \quad (2)$$

Where λ_1 and λ_2 are the eigenvalues given from the characteristic equation: $\det(\lambda Id - ZY) = 0$ Id is the identity matrix. The coefficients C_i (i=1-4) depend on voltages and currents available in source substation at the incident moment and the various boundary conditions, whereas α_i (i=1-6) are constants expressed by the relations system (3).

$$\alpha_1 = \frac{z_s\lambda_1^2 - \left(z_c z_s - z_{cs}^2\right) y_{cs}}{z_{cs}\lambda_1^2 - \left(z_c z_s - z_{cs}^2\right) y_{cs}} \quad , \quad \alpha_2 = \frac{z_s\lambda_2^2 - \left(z_c z_s - z_{cs}^2\right) y_{cs}}{z_{cs}\lambda_2^2 - \left(z_c z_s - z_{cs}^2\right) y_{cs}}$$
$$\alpha_3 = \frac{-\lambda_1\left(z_s - z_{cs}\alpha_1\right)}{\left(z_c z_s - z_{cs}^2\right)} \quad , \quad \alpha_4 = \frac{-\lambda_2\left(z_s - z_{cs}\alpha_2\right)}{\left(z_c z_s - z_{cs}^2\right)} \tag{3}$$
$$\alpha_5 = \frac{-\lambda_1\left(z_c\alpha_1 - z_{cs}\right)}{\left(z_c z_s - z_{cs}^2\right)} \quad , \quad \alpha_6 = \frac{-\lambda_2\left(z_c\alpha_2 - z_{cs}\right)}{\left(z_c z_s - z_{cs}^2\right)}$$

3. Prelocalization improvement approach

We assume a short circuit with the ground according to the configuration of figure 3. The fault impedances core-sheath (R_{cf}) and sheath-ground (R_{sf}) are supposed to be resistive. For the determination of the boundary conditions, we decompose the network, at the fault point (F), into upstream and downstream circuits. The upstream circuit extends from the sending-end to the fault point. The downstream circuit extends from the fault point to the receiving-end. These two circuits obey to equations of the system (2) with the boundary conditions of (4). As given; we obtain four equations on behalf of each circuit necessary to determine the unknown coefficients C_1, C_2, C_3 and C_4. It should be noted that the values $V_{cE}(0)$, $I_{cE}(0)$ et $I_{sE}(0)$ are given directly from the recordings of the incident moment available in sending-end, whereas the load impedance Z_R is calculated from the recordings just before the fault (in healthy state) and is supposed remaining unchanged during the short circuit [5].

Upstream circuit : $0 \le x \le d$

$$\begin{aligned} V_{cE}(0) &= V_c^m \\ I_{cE}(0) &= I_c^m \\ V_{sE}(0) &= -Z_n I_{sE}(0) \\ I_{sE}(0) &= I_s^m \end{aligned}$$

Downstream circuit: $0 \le y \le (l-d)$

$$\begin{aligned} V_{cE}(d) &= V_{cR}(0) \\ V_{sE}(d) &= V_{sR}(0) \\ V_{cR}(l-d) &= Z_R I_{cR}(l-d) \\ V_{sR}(l-d) &= Z_n I_{sR}(l-d) \end{aligned} \tag{4}$$

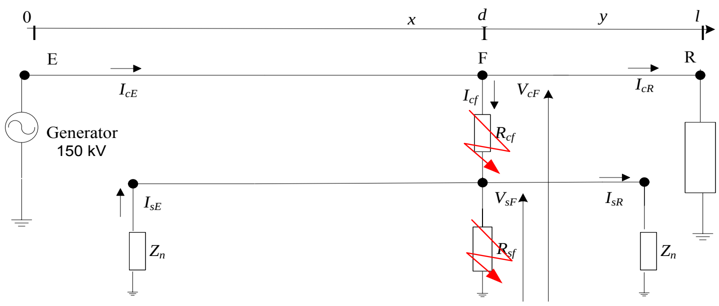

Fig.3. Core-sheath-ground fault network with impedances earthing

Due to a lack of measured data in the source side, these recordings are taken from the fault simulation in the environment of Simulink-SimPower Systems of Matlab. The sheath behavior at fault point is described by the equation (9).

$$f(d,R_{sf}) = V_{sE}(d) - R_{sf}\left(I_{cE}(d) - I_{cR}(0) \right) - R_{sf}\left(I_{sE}(d) - I_{sR}(0) \right) = 0 \tag{5}$$

Fault equation (5) is solved by two methods: one analytical and another numerical.

3.1. Analytical method

The permanent mode of the fault, governed by (5), can be presented in the form of (6).

$$R_{sf}(d) = \frac{V_{sE}(d)}{I_{cE}(d) - I_{cR}(0) + I_{sE}(d) - I_{sR}(0)} \tag{6}$$

At fault, the stable operation mode of the network will be assured if the relation (6) is satisfied, i.e. if the sheath-ground fault resistance (R_{sf}) calculated according to (6) obeys the two conditions (7) and (8) where Re(.) and Im(.) indicate respectively the real and imaginary parts of the quantity considered.

$$\mathrm{Re}\left[R_{sf}(d) \right] > 0 \tag{7}$$

$$\mathrm{Im}\left[R_{sf}(d) \right] = 0 \tag{8}$$

Knowing the final operation point, defined by the conditions (7) and (8), we deduce the value of the fault distance *d*. The value of the core-sheath fault resistance R_{cf} is calculated by (9).

$$R_{cf} = \frac{V_{cE}(d) - V_{sE}(d)}{I_{cE}(d) - I_{cR}(0)} \tag{9}$$

3.2. Numerical method

This method based on the well known Newton Raphson iterative method is given in details in [9].

4. Results and discussions

To show the compensation inductance influence on the fault prelocalization precision, we simulated a defaults variety (frank and resistive) with and without inductance L_n for two cable lengths. By taking into account the fault nature and the cable length, we analyzed the algorithm robustness to the variation of the fault location. We simulated frank and resistive faults with the software Simulink-SimPowerSystems of Matlab at a distance d_r from the source ($0 < d_r < l$) in both cases of short cable with l = 700m and long cable with l=15400m. The relative error of the calculated distance d compared to the real distance d_r is expressed by (10).

$$\varepsilon(\%) = 100\frac{d - d_r}{l} \tag{10}$$

4.1. Without compensation inductance

Figures 4 and 5 illustrate the obtained results and show well that the error varies according to the fault place and the fault nature represented by resistances R_{cf} and R_{sf}. When it stays lower than 3% for a short cable, it can reach the 11% for a long cable. Indeed, the error becomes significant for the resistive defaults, mainly in the long cable case, because of the transverse capacitive currents effect which reduce the current crossing the fault resistances [15]. Also the sheath- ground capacitance value increases with the cable length and can be considered as an in-feed source of electrical current [7] which deforms the estimated fault distance.

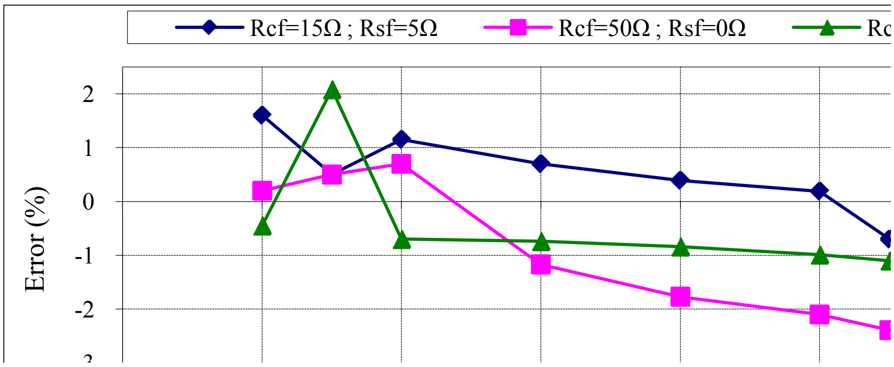

Fig.4. Distance error with different fault locations (l=700m)

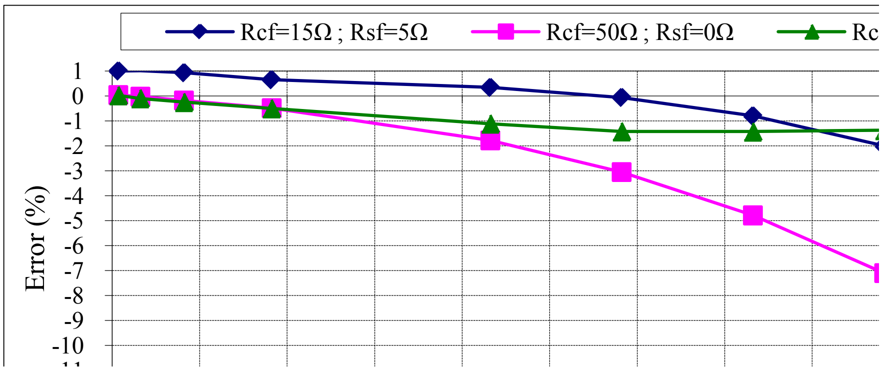

Fig.5. Distance error with different fault locations (l=15400m)

4.1. With compensation inductance

An error of 11% for a cable of 15400 m length means an average error distance equal to 1694 m. This error is very significant and the results obtained are far from reality. In order to ameliorate this error, we introduce an inductance in the earthing system to increase the earthing impedance what compensate the capacitive current and favor the current return path through fault resistances. Figure 6 shows the results and confirms our approach. The maximum distance error doesn't exceed 2%.

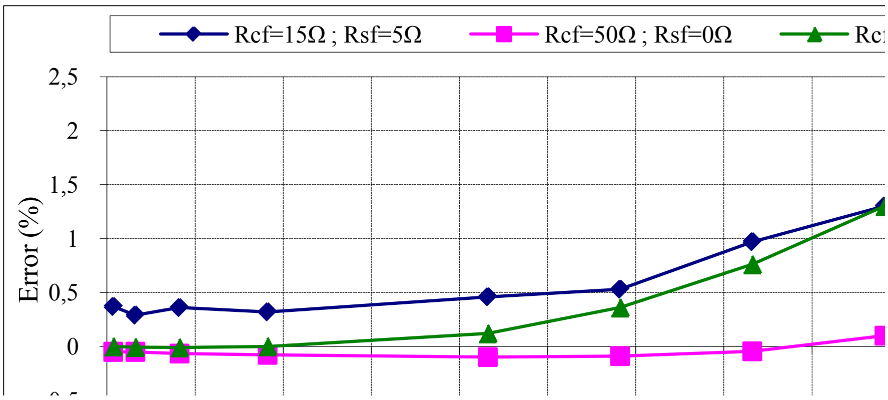

Fig.6. Improvement of distance error for long cable (*l*=15400m) by introducing a inductance in the system earthing

It is announced that fault equation (5) is solved by two methods: one analytical and another numerical. Then to compare the two methods, we simulated a resistive fault with Simulink-SimPowerSystems of Matlab at a distance d_r=100m and d_r=6050m of a cable with length l= 15400m. The obtained results are given in tables (1-2). The voltages and currents relating to the core and the sheath, the resistances and the distance from fault point are compared.

Table 1
Resistive default case ($R_{cf=}$15 Ω et R_{sf}=5 Ω) at d_r=100m.

Variables and Parameters		$I_{cE}(d)$	$I_{cR}(0)$	$I_{sE}(d)$	V_{cF}	R_c (Ω)	R_{sf} (Ω)	d (m)	ε (%)
Simulink-Simpower	Mod(A,kV)	8101	193.4	2080	150	15	5	100	
	Arg (°)	-4.57	17.4	123.7	-0.183				
Analytic method	Mod(A,kV)	8065.8	185.5	2070.4	150.7	15.1	4.9	157	0.37
	Arg (°)	-4.9	18.6	120.7	-2.9				
Numerical method	Mod(A,kV)	8066	193.7	2076.3	150.1	16	4.98	157.1	0.37
	Arg (°)	-4.77	18.1	120.8	-0.3				

Table 2
Resistive default case ($R_{cf=}$15 Ω et R_{sf}=5 Ω) at d_r=6050m.

Variables and Parameters		$I_{cE}(d)$	$I_{cR}(0)$	$I_{sE}(d)$	V_{cF}	R_c (Ω)	R_{sf} (Ω)	d (m)	ε (%)
Simulink-Simpower	Mod	8265	180.9	2484	147.8	15	5	6050	
	Arg (°)	-13.2	-11.2	146.4	-9.6				
Analytic method	Mod	8233	226.9	2433	154 .8	15.13	4.98	6122	0.47
	Arg (°)	-14	-56.17	144.6	-27.5				
Numerical method	Mod	8235	180.3	2491	148	15.3	4.98	6121	0.46
	Arg (°)	-13.8	-8.1	144.6	-10				

We can confirm that voltages and currents obtained by the two suggested methods and the software Simulink-SimPowerSystems are in perfect agreement along the cable independently of the fault position *F*.

5. Conclusion

In this study, we have presented a prelocalization improvement approach by introducing a compensation inductance in the earthing system to ameliorate the fault distance precision in the resistive fault cases affecting the long single phase underground cables.
Several simulation scenarios, with and without compensation inductance, using the developed approach are presented and compared with the obtained results with the software SimPowerSystems of Matlab.

We note amelioration on the fault distance precision. In fact, the error, which reached 11% without compensation inductance, did not exceed 2% with compensate inductance.

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