A Cost-effective Solution for Clearing High-Impedance Ground-Faults in Over-Head Low-Voltage Lines

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***Abstract*-- Downed distribution conductors in overhead distribution systems, may not be a concern for equipment, but greatly challenge the safety of persons, as well as the integrity of properties. Standard overcurrent protective devices may not be able to detect the magnitudes of currents resulting from high-impedance ground- faults. Sophisticated relays able to detect high-impedance ground-faults have been available to electric utilities. However, their implementation is rather uncommon, especially in developing countries, most likely due to their costs. In this paper, the authors formalize the problem, and propose a possible cost-effective solution for low-voltage over-head lines with neutral wire. This solution consists of a metal hook underneath the line conductors, attached to the pole, and connected to the neutral wire. In the case of a falling line, the hook would be contacted and a line-to-neutral short circuit would occur; this would positively activate existing standard over-current devices, which can therefore disconnect the supply. Costs related to the installation of the device to existing overhead lines are herein analyzed. The effectiveness of the proposed solutions for two different voltage levels (400V in European countries and 240V in the US) is also discussed.**

***Index Terms*-- High-Impedance Ground fault; fault protection; metal hook; over-head lines; short-circuit currents.**

I. INTRODUCTION

44% of all electrical fatalities from 1992 through 2010 were caused by contact with overhead power lines, both low-voltage and high-voltage [1]. The statistics also comprise accidents involving energized downed conductors, including drop-down services to dwelling units.

In the case of collapse of energized power lines on the ground, overcurrent protective devices may not be able to detect the magnitudes of the current, due to the possible high-impedance contact with the soil [2]. As an example, Table I lists some typical values of ground-fault currents depending on the surface with the downed conductors comes into contact [3].

In literature, several research studies concerning ground-fault protection [4], and high-impedance faults detection can be found. In [5], the authors propose a magnetic sensor based analysis for 0.44 kV distribution networks to identify high-impedance faults. Magnetic sensors are immune to non-homogeneous line conductors, ground resistance and other factors that generally influence the detection of high-impedance faults. This method is based on magnetic field measurements in the proximity of the conductors and must take into account the network configuration (e.g. nodes, parallel lines, etc.).

In [6] a method for detection and location of high-impedance faults based on smart meters placed at strategic points along the feeder and using a voltage unbalance based approach is proposed.

In [7] the authors propose a Wavelet Transform and data mining based Decision Tree model for high impedance faults detection in distribution networks. Wavelet Transform are used for decomposing the current signal and extracting significant features while the data mining model reduces the features of the signal, and is used for distinguishing between high-impedance and low-impedance faults.

Wavelet transform is applied also in [8] for detecting in real time the transient induced by high-impedance faults. The authors of [8] assess the performance of the proposed method by using data related to real and simulated faults.

TABLE I. TYPICAL VALUES FOR HIGH-IMPEDANCE GROUND-FAULT CURRENT.

Soil Surface	Ground-Fault Current Value [A]
Asphalt (Dry)	0
Asphalt (Wet)	1
Concrete (Non-reinforced)	10
Concrete (Reinforced)	70
Sand (Dry)	0
Sand (Wet)	5
Sod (Dry)	10
Sod (Wet)	50

In lieu of the aforementioned sophisticated protective devices detecting high-impedance faults [9], in this paper the authors introduce a cost-effective solution consisting of a metal hook placed underneath the line conductors, attached to the low-voltage over-head lines poles, and connected to the neutral wire. In the case of a falling line, the hook would be contacted by the wire, and a line-to-neutral short circuit would occur. This would positively activate existing standard over-current devices, which can therefore disconnect the supply, and de-energize the downed conductor.

A possible cost-effective solution includes a metal hook of proper span underneath the line conductors, attached to the pole, and connected to the neutral wire. This arrangement would cause a line-to-neutral short circuit, positively activating existing over-current devices, which can therefore disconnect the supply, and de-energize the downed conductor. The authors analyze the problem for different possible configurations of the grounding of the neutral wire.

II. PROBLEM FORMULATION

Consider the circuit in Fig. 1 representing a MV/LV transformer supplying one LV line experiencing the interruption of line conductor L1.

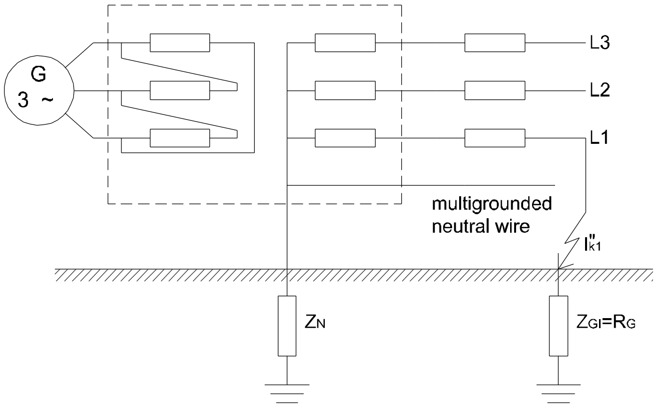

Fig. 1. Single line to ground fault due to a line conductor interruption.

The broken conductor in contact with the soil behaves as a ground electrode having a resistance to ground R_G. The fault current can be expressed as in [10]:

$$I''_{k1} = \frac{\sqrt{3} c U_n}{\left| 2\underline{Z}_{(1)} + \underline{Z}_{(0)} + 3\underline{Z}_N + 3Z_{GI} \right|} \tag{1}$$

where:

- c is the voltage factor
- U_n is the nominal LV phase-to-phase voltage;
- $Z_{(1)}$ the positive-sequence short circuit impedance at the fault location;
- $Z_{(0)}$ the zero-sequence short circuit impedance at the fault location;
- Z_N is the transformer's neutral point earthing impedance;
- Z_{GI} is impedance to ground at the point of contact between the interrupted conductor and the earth.

In Equation (1), we have:

$$\underline{Z}_{(1)} = \underline{Z}_{(1)T} + \underline{Z}_{(1)LF} \tag{2}$$

$$\underline{Z}_{(0)} = \underline{Z}_{(0)T} + \underline{Z}_{(0)LF} \tag{3}$$

where:

- $Z_{(1)T}$ and $Z_{(0)T}$ are the positive-sequence and zero-sequence short circuit impedance of the transformer, respectively;
- $Z_{(1)LF}$ and $Z_{(0)LF}$ are the positive-sequence and zero-sequence impedance of the LV line from the transformer to the interruption location, respectively;

By using a hook connected to the same ground of the neutral conductor (Fig. 2), the impedance Z_{GI} appearing in equation (1), varies as it follows:

$$\underline{Z}_{GI} = \left(\frac{1}{R_T} + \frac{1}{\underline{Z}_{Pn,L}} + \frac{1}{\underline{Z}_{Pn,R}} \right)^{-1} \tag{4}$$

where:

- R_T is the footing resistance of the line tower just upwards the interruption;
- $Z_{pn,L}$ and $Z_{pn,R}$ are the equivalent impedance of the finite chain composed of the neutral conductor impedance and the footing impedance of the tower, upwards and downwards the interruption, respectively, calculated according to [10].

III. CASE STUDY

Consider the LV over-head line represented in Fig. 3 where a phase conductor breaks and falls to the ground between poles 2 and 3. The contact between the broken conductor and the hook determinates a short circuit with a fault current given by (1).

Table II reports the main features of the pole-mounted transformer supplying the LV line and of the line itself.

Two cases are herein discussed:

1. broken conductor without hook;
2. broken conductor with hook and multi-grounded neutral wire.

In the first case, an impedance to ground $Z_{GI} = 100\ \Omega$ is considered. In the second case, due to the contact of the broken conductor with the hook, and due to the presence of the multi-grounded neutral, the impedance-to-ground, calculated with (4), is $Z_{GI} = 0.0151+0.0019j\ \Omega$.

TABLE II. DATA OF THE SYSTEM SHOWN IN FIG. 3.

Transformer's rated power A_n	100 kVA
Transformer's rated voltage ratio k_n	20/0.4 kV/kV
Transformer's short-circuit impedance $Z_{1(T)}=Z_{(0)T}$	0.0604+0.0304j Ω
Transformer's neutral point grounding impedance Z_N	0.2 Ω
Mean distance L between poles	30 m
Total length of the LV line	300 m
Number N of poles (except the transformer's pole)	10
Cross-Section S of line conductors	4x1x16 mm^2
Distributed positive-sequence impedance of the line $z_{(1)L}$	1.11+0.3j Ω/m
Distributed zero-sequence impedance of the line $z_{(0)L}$	1.26+0.437j Ω/m
Mean footing resistance of the poles R_T	20 Ω

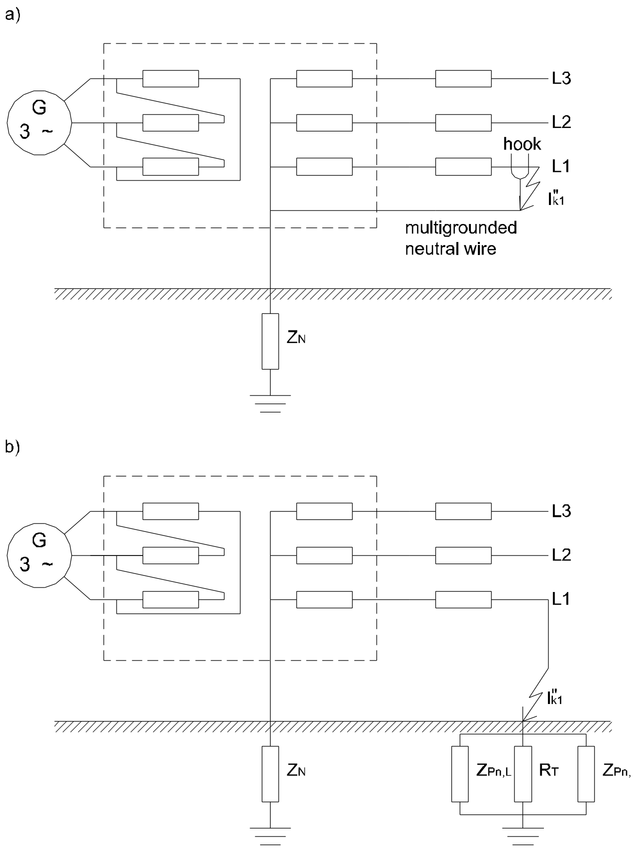

Fig. 2. a) Single line to ground fault due to a phase conductor interruption in presence of hooks on the line towers. b) Equivalent circuit model for studying the fault.

Consequently, the fault current's calculation yields the following results in the two cases:

Case 1: $I''_{k1} = 2.41$ A;
Case 2: $I''_{k1} = 746.24$ A.

We assume that the overhead line is protected by a 50 A rated circuit breaker, and that the load does not exceed 35 kVA. The circuit breaker is assumed to be in compliance with [11], with the typical trip curve of Fig. 4 [12]; the two fault clearing times that have been considered are:

1. t_F = infinite (the hook is not present);
2. t_F = 15 ms (the hook is present).

In the first case, the standard circuit breaker installed at the beginning of the overhead LV line cannot detect and interrupt the fault current. The downed conductor becomes a source of hazards for persons in its proximity.

In the second case, the circuit breaker can interrupt the circuit in few tens of milliseconds.

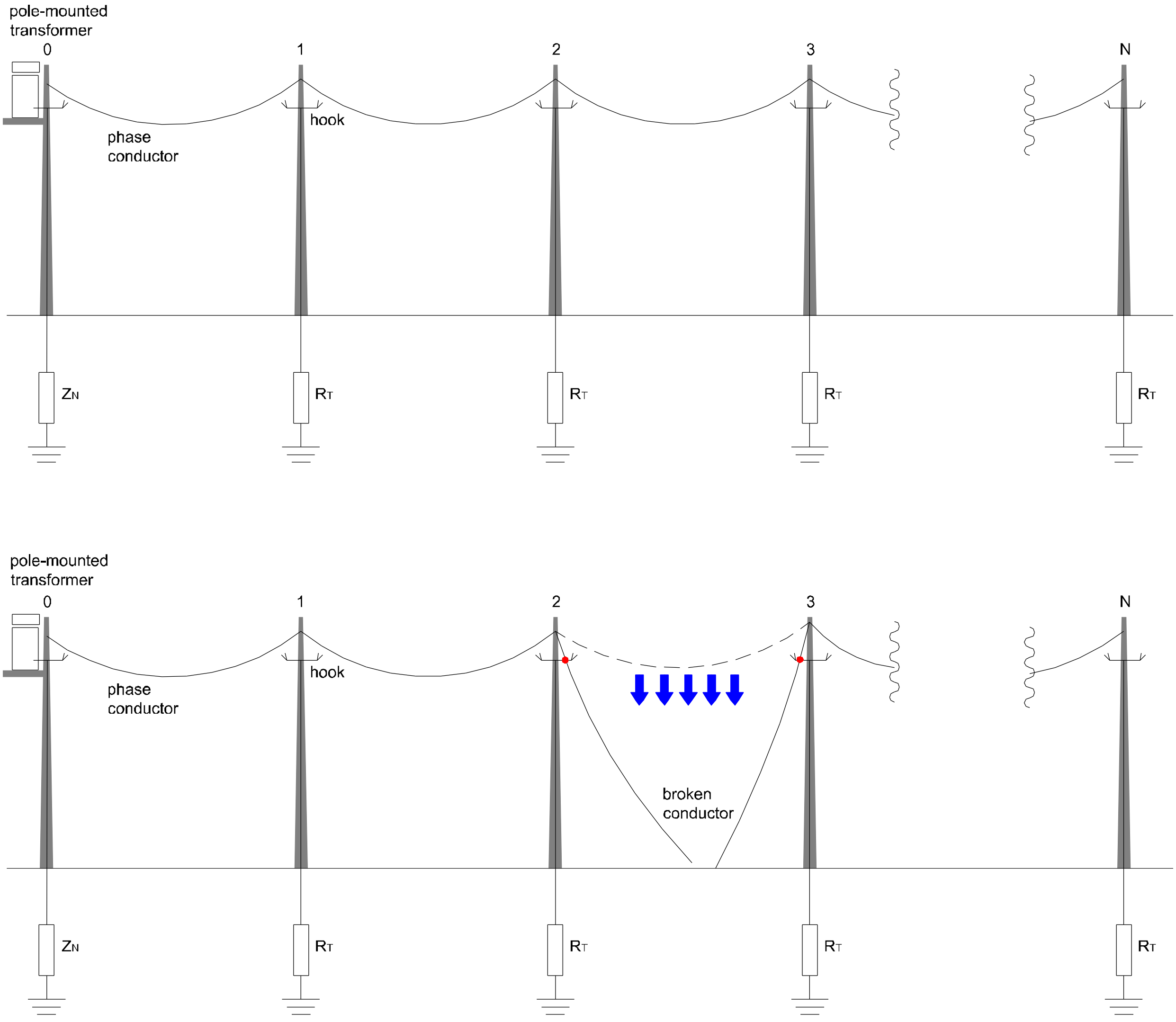

Fig. 3. Contact between the broken phase conductor and the hook.

IV. THERMAL SIZE OF THE HOOK

The sizing of the hook has been performed based on thermal strength, according to [13]. The cross section of the hook is calculated as:

$$S = \frac{I''_{k1}}{K}\cdot\sqrt{\frac{t_f}{\ln\frac{\Theta_f+\beta}{\Theta_i+\beta}}} \qquad (5)$$

where:

- S is the cross-section in mm²;
- I''_{k1} is the fault current in amperes (RMS value);
- t_f is the duration of the fault current in seconds;
- K is a constant depending on the material of the current-carrying component, given in Table D.1 of [13];
- β is the reciprocal of the temperature coefficient of resistance of the current-carrying component at 0 °C;
- Θ_i the initial temperature of air in Celsius degrees;
- Θ_f the final temperature of hook in Celsius degrees.

The hook can be conservatively sized considering the highest phase-to-neutral current, and a fault duration of 0.1 s. Assuming a fault at the beginning of the LV line, in the case of Dy$_n$ transformer, the highest phase-to-neutral short circuit current I''_{k1}, calculated by neglecting the contribution of the MV network, is given by:

$$I''_{k1} = \frac{c\cdot\sqrt{3}\cdot U_n}{\left|2\underline{Z}_{(1)T}+\underline{Z}_{(0)T}\right|} = \frac{c\cdot A_n}{\sqrt{3}\cdot\%z\cdot U_n}\cdot 100 \qquad (6)$$

where:

- A_n is the nominal power of the transformer in kVA;

- *%z* is the percentage short-circuit impedance of the transformer.

MV/LV pole-mounted transformers usually have a rated apparent power ranging between 50 to 400 kVA, and percentage short-circuit impedances ranging between 4% to 6%. We assume for the calculations the values given in Table III; the short-circuit current, the hook cross-section and the hook diameter *d* are reported in Table IV to VII, as a function of the transformer rating and for two different values of the LV rated voltage: 400V (European standard) and 240V (US standard).

TABLE III. DATA FOR CALCULATING THE HOOK'S CROSS SECTION.

Material	Steel
Cross-section shape	Circular
Initial ambient temperature Θ_i	40°C
Final hook's temperature Θ_f	300°C
Coefficient β	202 °C
Constant K	$78\ A\sqrt{s}\ /mm^2$
Voltage factor c	1.05
Nominal voltage U_n	400 V

TABLE IV. HOOK'S CROSS SECTION (RATED VOLTAGE 400V - PERCENTAGE SHORT CIRCUIT IMPEDANCE EQUAL TO 4%).

A_n [kVA]	I''_{k1} [A]	S [mm^2]	d [mm]
50	1897	9.00	3.39
100	3793	18.00	4.79
160	6069	28.81	6.06
200	7587	36.01	6.77
315	11949	56.71	8.50
400	15173	72.02	9.58

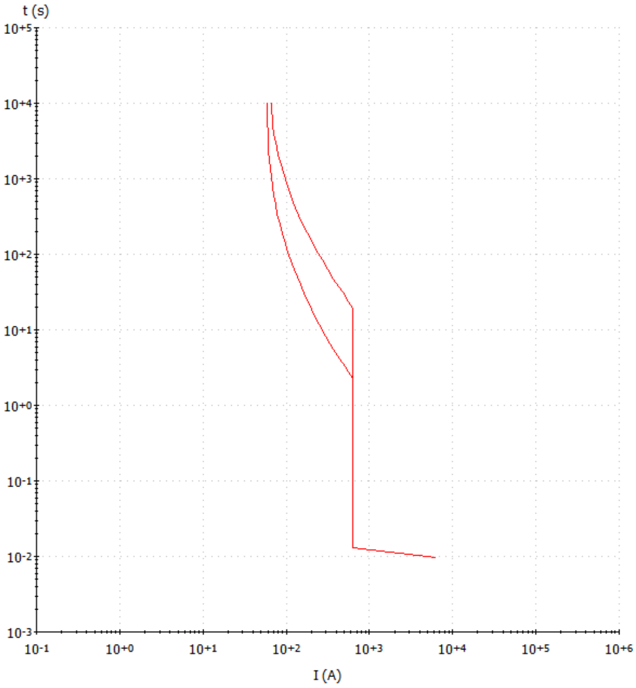

Fig. 4. Trip curves of the automatic circuit breaker protecting the overhead lineor [11] [12].

TABLE V. HOOK'S CROSS SECTION (RATED VOLTAGE 400V - PERCENTAGE SHORT CIRCUIT IMPEDANCE EQUAL TO 6%).

A_n [kVA]	I''_{k1} [A]	S [mm^2]	d [mm]
50	1264	6.00	2.76
100	2529	12.00	3.91
160	4046	19.20	4.94
200	5058	24.01	5.53
315	7966	37.81	6.94
400	10116	48.01	7.82

TABLE VI. HOOK'S CROSS SECTION (RATED VOLTAGE 240V - PERCENTAGE SHORT CIRCUIT IMPEDANCE EQUAL TO 4%).

A_n [kVA]	I''_{k1} [A]	S [mm^2]	d [mm]
50	3161	15.00	4.37
100	6322	30.01	6.18
160	10116	48.01	7.82
200	12645	60.01	8.74
315	19915	94.52	10.97
400	25289	120.03	12.36

TABLE VII. HOOK’S CROSS SECTION (RATED VOLTAGE 240V - PERCENTAGE SHORT CIRCUIT IMPEDANCE EQUAL TO 6%).

A_n [kVA]	I''_{k1} [A]	S [mm^2]	d [mm]
50	2107	10.00	3.57
100	4215	20.00	5.05
160	6744	32.01	6.38
200	8430	40.01	7.14
315	13277	63.01	8.96
400	16859	80.02	10.09

The hook will approximately require 1.5 m of steel, with, in the worst case, a cross-section assumed equal to 75 mm^2 in a 400V network; thus the total mass can be estimated to be about 0.89 kg of steel for each hook, with a cost of about 5.5 €.

For rated voltage equal to 240 V, the hook’s cross-section is assumed equal to 120 mm^2, with an estimated mass of about 1.42 kg of steel, and a cost of about 9 €.

V. CONCLUSION

This work is based on [14] where the authors have presented a low-cost high-efficiency solution for the prompt de-energization of over-head LV lines possibly under high-impedance ground-fault conditions. This solution is an effective substitution of sophisticated protective relays.

The metal hook is attached to the pole underneath the line conductors, and is connected to the neutral wire. In the case of rupture of the line conductor, the falling conductor would come into contact with the hook, and cause a line-to-neutral short circuit, positively activating existing standard over-current relays; the disconnection of the supply is therefore guaranteed.

The physical dimensions of the hook have been conservatively calculated by considering the highest phase-to-neutral current, and for a fault duration of 0.1 s

The installation of the hook on the poles is not labor intensive, and the actual cost of the material is less than 9 € in the worst case. Although simple, this arrangement provides an effective solution to prevent touch voltages caused by energized downed-conductors, and can increase the electrical safety of persons, and save lives. The hook installation is a sustainable and prompt solution also in developing countries, where LV distribution lines are typically over-head.

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