SPEED VERSUS SENSITIVITY IN EARTH FAULT PROTECTION REGARDING HUMAN SAFETY IN AERIAL MV NETWORKS

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ABSTRACT

This paper addresses the protection of aerial medium voltage network regarding the human safety aspect. Several situations that can endanger human safety are analyzed and a correlation between dangerous fault currents and fibrillation thresholds for persons is derived.
A recommendation for power system protection regarding ground current is made. It consists of a 2 step protection with a first step set to clear faults with low currents with no special constraints on time and a second step set up for higher currents in less than 0,2s.Coordination of protections needs to be addressed in a per case basis.

INTRODUCTION

The earth fault protection in Portugal was historically based on French standards and had defined a low current setting of about 0,6A and a long tripping time plus a higher setting with a smaller tripping time (coordinated with the other protections in the network). Some times the requirement for sensitivity has even been defined as a high fault resistance detection capability, which has led to still smaller current settings for lower voltage levels.
Recently, in order to align itself with the good practices and international trends, especially regarding methodologies and Quality of Service, EDP launched several projects in a wide research program.
Although the amount of sensitive earth-faults tripping may be small when compared to the total number of interruptions due to protection functions, it was considered important to address all relevant aspects of the required earth-fault sensitivity in order to determine the possibility of increasing the operational settings.
A research was performed to analyze all situations regarding human safety in normal operation of a medium voltage network.
The cases of Direct contacts, Indirect contacts and Broken Conductors were analyzed from a human safety point of view and some values of allowable short circuit current magnitudes and durations were attained.

HUMAN BODY TOLERANCE TO ELECTRIC CURRENT

Ventricular fibrillation is the most dangerous effect of electric current since it occurs for low current amplitudes. Both IEC and IEEE have different ways to deal with this physiological effect.
The IEEE uses the formulae derived by Dalziel in 1969 while the IEC established its criteria on the work done by Biegelmeier in 1980 ([6]).
The IEC criteria will be used in this paper.
In Fig.1 there are 3 curves (c1, c2 and c3) that express the probability of ventricular fibrillation for 5% of people (c1), 50% (c2) and 95% (c3). For all the 3 curves it is possible to establish the following behavior: the human body can withstand about 10 times more current for short durations (<0,2s) than for longer times (>5s).

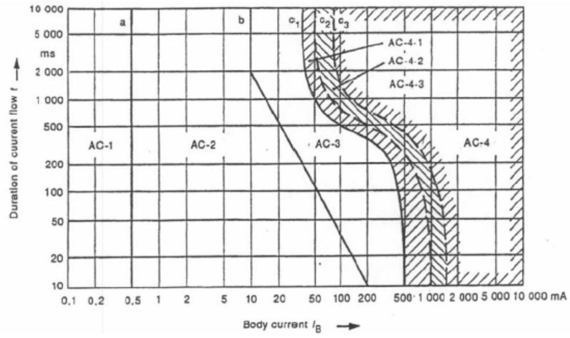

Fig. 1 – Fibrillation curves (c1, c2, c3) according to IEC 60479-1

It is also referred in [1] that the heart is only vulnerable to fibrillation during 1/3 of its cycle and if a current, even with high amplitude, is only present for 0,2s there is a low probability of fibrillation occurrence.

DIRECT CONTACTS

A direct contact between an active part of the electric distribution system and a person, despite being an unlikely event, can occur. However there are measures, other than protective relaying, in place to prevent these contacts like the physical separation between the active parts of the power system and zones reachable by the public in general (ex.: power lines height).
In the event of an accidental electrocution the current that passes through the human body is much larger than the 1,5A value which is required to cause the death to 95% of the people, according to [1]. Also the minimum current needed to kill a human is about 0,04A which is much less than even the usual residual currents resulting from network unbalance and which limits the protection sensitivity. (For residual current we understand the zero sequence current of a line which can be measured through current transformers – either a window CT or in the neutral of three phase CTs).
The only contribution that a protection approach can adopt to increase the probability of survival for a direct contact is to quickly disconnect the line. The recommend time frame is

0,2s, according to [1].
From a direct contact point of view it is desirable to have fast (or instantaneous) tripping for high earth currents.

INDIRECT CONTACTS

An indirect contact between a person and a part of the power distribution system is formed in the case of a person touching a faulted pole.

Touch Voltage near a MV pole

The case of a person touching a faulted pole is represented in figure 2.
Due to a fault, the electric potential around the pole increases and a person touching it is subjected to a voltage difference, which will cause a current to pass through her/his body. This current is expressed by

$$I_H = \frac{V_{touch}}{R_{H_{eq}}} \quad (1)$$

Where: I_H – human body current; V_{touch} – touch voltage; R_{Heq} – equivalent human body resistance.

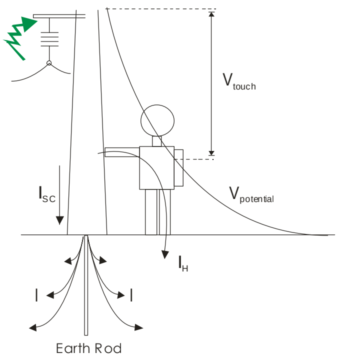

Fig. 2 – Touch voltage due to a fault to pole

The equivalent human body resistance can be decomposed in several variables.

$$V_{touch} = \left[R_H + 0,5\left(R_{foot} + R_{shoe}\right)\right] I_H \quad (2)$$

Where: R_H – human body resistance; R_{foot} – resistance of foot contact to ground (3ρ according to [2]); R_{shoe} – shoe resistance.

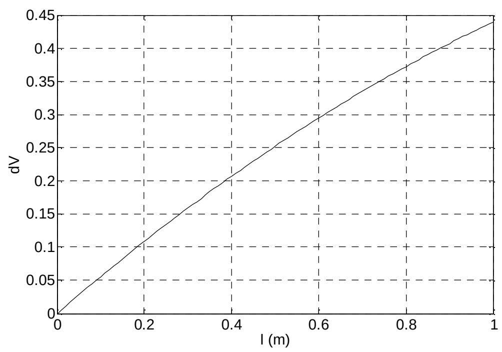

Fig. 3 –Potential difference from the ground potential rise variation with arm length

The touch voltage can also be expressed by equation (3).

$$V_{touch} = R_{pole}(r) I_{SC} \Delta V(l) \quad (3)$$

Where: R_{pole} – pole earthing resistance; ρ – soil resistivity; I_{SC} – short circuit current to pole; ΔV – potential difference from the ground potential rise (pu); l – arm length.
For the Portuguese case the ΔV variation with arm length is represented in the last figure.
The pole resistance can be determined by a geometry factor (k) calculated according to the earthing method of the pole. For the Portuguese case it is 0,146m^{-1}.

$$R_{pole} = k r \quad (\Omega) \quad (4)$$

Replacing equations (2) and (3) in (4) the following equation is achieved:

$$I_{SC} = \frac{R_H + 0,5\left(3r + R_{shoe}\right)}{k r \Delta V(l)} I_H \quad (5)$$

Risk Analysis

In order to evaluate the dangerous level of a current which must be detected by the protection system, a risk analysis has to be performed. This analysis is conducted to determine dangerous permanent currents and short time fault currents to poles. Equation (5) is used in this analysis.

Acceptable Risk
The acceptable risk used for this analysis was 0,1%. This means a risk of severe injury for only 1 in 1000 events of a person touching a pole while the pole is carrying a fault current to ground.

Soil Resistivity (ρ)
The soil electric resistivity is one of the main factors in determining the pole's potential rise due to the fault.
Because of the various types of soil that exist in Portugal a probability function must be considered. The mean soil resistivity for Portugal is commonly accepted as 100Ωm. The worst soils have a resistivity of about 5000Ωm.

Arm Length (l)
In figure 2 it can be seen that the touch voltage depends on the distance between the pole and the person's feet. That distance is given by the length of the arm.
CENELEC set this distance at 1m while the IEEE value is 0,8m. Both of these values are considered pessimistic by the referring organizations. A value between 0m and 0,8m would be more probable for an actual situation.
It is assumed a uniform probabilistic distribution for this variable between 0m and 1m.

Human Body Resistance (R_H)
The IEEE assumes this value to be 1000Ω.
For IEC this value varies with the applied voltage to the human body and the physical characteristics of each person. For dangerous voltages the minimum resistance for 5% of the

population is 1000Ω; for 50% of the population is 1350Ω; and for 95% it is 2125Ω.
The IEC values will be used because they are derived from actual experiments involving people and are therefore more detailed.
The IEC does not refer the type of probability distribution for the human body resistance. A normal distribution with a mean value of 1350Ω and a standard deviation of 212Ω was selected.

Shoe Resistance (R_{shoe})
The presence of shoes has the capability of reducing the human body current to a very low value. The IEEE and the IEC do not consider the effect of shoes although they have a significant influence on limiting the current passing through the human body. The main concern of these standards is the design of power system installations for long lives and not risk assessment for an earth fault.
Some typical values for shoe resistance are:

- Leather shoe sole (wet): 5kΩ to 20kΩ;
- Leather shoe sole (dry): 100kΩ to 500kΩ;
- Rubber shoe sole: 20MΩ

There is no data regarding the insulation breakdown voltage for footwear.
For risk analysis it will be assumed that 5% of the persons will be barefooted (a pessimistic approach nowadays) while the other 95% will be wearing shoes with a uniform resistance between 5kΩ to 100kΩ.

Human body tolerance to electric current (short time)
Reference [1] establishes that for short times (<0,2s) of applied current 95% of people can withstand 0,35A, 50% of people 0,5A and 5% of people 1,00A. There is no reference to the type of probabilistic distribution that should be used. In this case a normal distribution will be used which describes the mean value and the 95% (0,35A) value of withstand current.

Results (short time)
The risk analysis was conducted using the Monte Carlo method on 6 million random samples. The results are shown in the next figure.

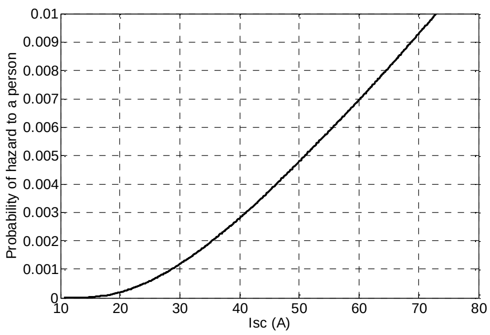

Fig. 4 – Relation between the probability of hazard and fault current (Short Time)

The selected acceptable risk of 0,1% is achieved by making sure that all faults with a magnitude higher than 30A are cleared in less than 0,2s.

Human body tolerance to electric current (long time)
For longer times (>3s) the human body tolerance to electric current is greatly reduced. For 95% of the people this is 0,04A, for 50% it is 0,05A and for 5% this value is 0,09A. A Gaussian probability distribution with a mean value of 0,05A and standard deviation determined so that 95% of the people can withstand 0,04A is assumed.

Results (long time)
This analysis is intended to determine the maximum residual current that can be allowed in the network indefinitely. The results are shown in figure 5.
By clearing all faults with a residual current of 3A the acceptable risk of 0,1% is achieved.
However it is wise to have a 2,5A selected current due to the thermal capacity of the grounding reactor and to account for relaying inaccuracies.

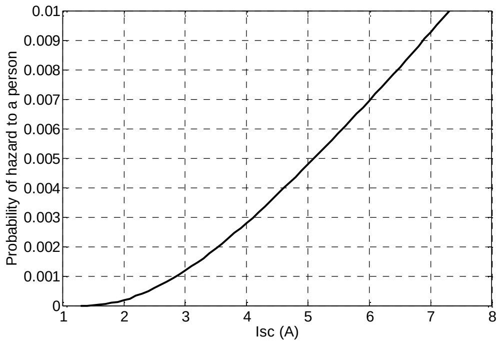

Fig. 5 – Relation between the probability of hazard and fault current (long time)

An interesting corollary of these results is that a MV/LV transformer may be safely protected by a set of independent fuses in its MV side provided that its rated primary current does not exceed 7,5 A. This is because if a fault to earth through the earth connection of the (pole-mounted) transformer is interrupted by a fuse, the persisting fault current will not exceed 2,5 A [8], and that current yields a minor risk for any person touching the pole.

BROKEN CONDUCTORS

A broken conductor can be a very difficult situation to detect especially if the conductor is in contact with the ground from the load side. For more information regarding broken conductor please refer to a companion paper presented to this conference [8].
For a direct touch there is no way to insure human safety because the fault current prior to the contact can be almost zero, while according to [1] 0,04A may be sufficient to kill a person. These currents cannot be distinguished from the usual residual current resulting from network unbalance.

Step voltages near the broken conductor are very low if a person is about 1m apart from the conductor (Fig. 6). The real danger arises for a person actually stepping on the conductor. If the maximum residual current in the network is limited to 2,5A, even if a person steps on the broken conductor (uniform soil assumed) only a percentage of those 2,5A would pass through the person. Since the step voltage is far less dangerous than touch voltage there is a large probability for a person to survive.

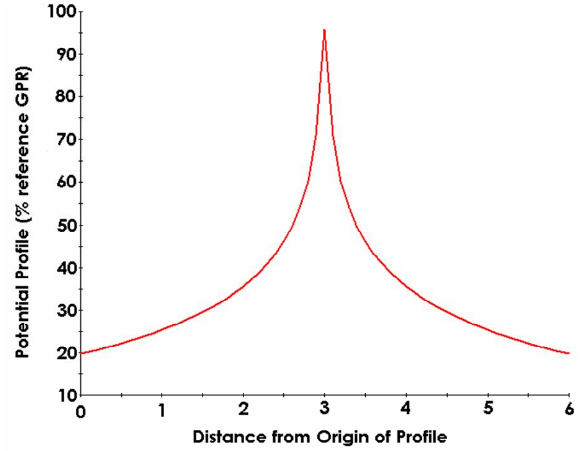

Fig. 6 – Electric Potential near a broken conductor

Despite being a dangerous situation for human safety, the detection of broken conductors cannot be all achieved by monitoring residual currents. Other technologies have to be developed for the detection of broken conductors.

CONCLUSIONS

The low residual current settings used for protective relaying of MV networks can be increased to a value of 3A without endangering human safety. However, due to the thermal capacity of the neutral reactor and accounting for protection inaccuracies, a setting of 2,5A is advisable. Since this protection is mostly directed towards indirect human touches, speed is not a fundamental issue.

However, a second protection element must exist to clear faults with a current higher than 30A in less that 0,2s. This setting is also in line with results concerning direct contacts for which it is desirable to rapidly clear faults with high amplitude of current.

For this analysis, only human safety factors were considered. There are other factors to account for such as coordination which have to be addressed in a per case basis.

In countries, other than Portugal, some of the assumptions made with respect to pole grounding and neutral connections may not hold.

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