EVALUATION OF PROTECTION APPROACHES TO DETECT BROKEN CONDUCTORS IN DISTRIBUTION NETWORKS

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ABSTRACT

Broken conductors in aerial lines are a type of fault some times very hard to detect in distribution networks.
Traditional approaches to detect broken conductors have been based on some type of zero current based relaying, but the limitations of such a tradition are well known. Because of that, in recent years and with the arise of modern multi-function relays, some hope has been directed towards conventional protection principles based not on zero currents, but on negative currents.
In this paper the two types of principles, based on zero and on negative currents, are evaluated, with a real network supporting their comparison.
The results show that as a rule for distribution networks negative current based relaying is less effectif than the traditional zero currents based approach to detect ground faults with broken conductors. Only for broken lines not touching soil and carrying significant load currents negative-based protection provides some improvement .

INTRODUCTION

Broken conductors in aerial lines are a type of fault that some times may be very hard to detect in distribution networks.
Traditional approaches to detect broken conductors have been based on some type of zero current based protection [1], but the limitations of such a tradition are well known. Because of that, in recent years and with the arise of modern multi-function relays, some hope has been turned to still conventional protection principles but based on the negative currents, not on zero currents.
In what follows, the two types of principles, based on zero and on negative currents, are evaluated.
Firstly, three types of broken conductor conditions are defined, and for each one the expressions for zero and for negative currents are reminded.
Next, aspects limiting the sensitivity of protection principles applying either zero or negative currents are listed in order to define optimal settings for relaying.
A real small network is then presented as a test bed for the two protection principles, which are then evaluated in their theoretical effectiveness.

PROBLEM STATEMENT

Most often a conductor of an aerial line breaks near a suspension point, where the mechanical stress is stronger. As a result, the conductor usually falls down, but it remains connected to one of its ends. Which suspension point is broken is a random hazard, but the electrical consequences are quite different depending on that.
It also happens that a conductor breaks near the suspension point but it does not fall down, or it does but on very resistive soils (such as dry asphalt, dry concrete, etc). These three conditions – receiving end connected and conductor fallen on conductive soil, conductor not on soil or on highly-resistive soil, and conductor with its sending end connected, will be named hereafter and respectively A, A* and B and are illustrated in figure 1.

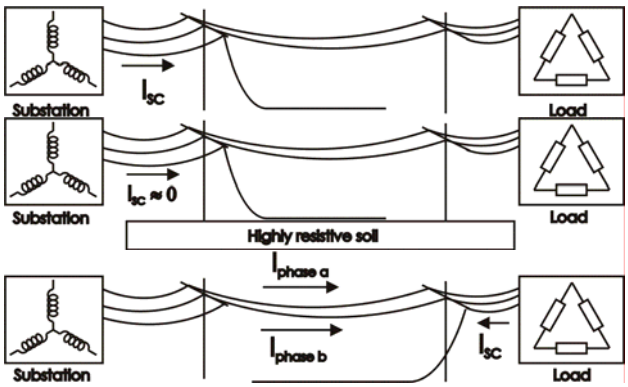

Figure 1: Broken conductors suspended from its receiving end on a good and on a badly conducting soil (conditions A and A), and suspended from its sending end (condition B).*

MATHEMATICAL EXPRESSIONS

Condition A: conductor suspended from its receiving end, fallen on good conducting soil

For a broken conductor in condition A, there is a fault current which value is given by the well known expression:

$$\overline{I}_{fault} = \frac{\overline{E}_{+}^{s}}{R_{fault} + \dfrac{\overline{Z}_{+}^{s} + \overline{Z}_{-}^{s} + \overline{Z}_{0}^{s}}{3}} \qquad (1)$$

Where the superscript "s" stands for source, and R_{fault}, the fault resistance, is the equivalent resistance of the arc plus the soil. As seen from the source side, when such a fault arises there are some changes in the sequence currents as follows:

$$\Delta\overline{I}_{+}^{s} = \overline{I}_{+}^{s} - \overline{I}_{+}^{s,pf} \simeq -\frac{1}{2}\overline{I}_{+}^{s,pf} + \frac{1}{3}\overline{I}_{fault} \qquad (2)$$

$$\Delta\overline{I}_{-}^{s} = \overline{I}_{-}^{s} \simeq -\frac{1}{2}\overline{I}_{+}^{s,pf} + \frac{1}{3}\overline{I}_{fault} = \Delta\overline{I}_{+}^{s} \qquad (3)$$

$$\Delta\overline{I}_{0}^{s} = \overline{I}_{0}^{s} \simeq \frac{1}{3}\overline{I}_{fault} \qquad (4)$$

where $\overline{I}_{+}^{s,pf}$ stands for the pre-fault balanced current, which depends on the load. For small fault resistances and a small source zero impedance, the fault current will usually be much larger than the pre-fault load current.

Condition A*: broken conductor not in touch with soil or fallen on highly-resistive soil

This condition may be expressed as a mathematical degeneration of expressions (1-4), for which there is no phase-to-ground fault current and:

$$\Delta\overline{I}_{+}^{s} = \overline{I}_{+}^{s} - \overline{I}_{+}^{s,pf} \simeq -\frac{1}{2}\overline{I}_{+}^{s,pf} \quad (5)$$

$$\Delta\overline{I}_{-}^{s} = \Delta\overline{I}_{+}^{s} \quad (6)$$

$$\Delta\overline{I}_{0}^{s} = \overline{I}_{0}^{s} \simeq 0 \quad (7)$$

Now, the pre-fault load current is the only independent variable determining the value of the changes on the positive and on the negative currents. Of course, if besides no phase-to-ground current there was no load before the conductor broke, there is no observable change in any sequence current from the source side and the fault can not be detected through any sequence current at the steady-state frequency.

Condition B: broken conductor suspended from its sending end, fallen on soil

For a broken conductor, condition B has about the same probability to occur as conditions A and A*, but now the sequence currents look differently than before. Their expressions are quite long for a general network, but they can be approximated by simpler expressions if the following assumptions hold, as they do for most distribution networks in Europe (with ungrounded MV loads side):

- Small short-circuit ratio (ratio between the load impedance, as seen from the source, and the source impedance);
- Similar negative and positive source impedances;
- Similar negative and positive load impedances. This assumption is not true for motors, but we will assume that three-phase motors are disconnected by their unbalance protections.

Under these assumptions, the following expressions hold:

$$\overline{I}_{fault} \simeq \frac{\dfrac{\overline{I}_{+}^{s,pf}}{3}}{1+2\dfrac{R_{fault}}{3\overline{Z}_{load}}} \quad (8)$$

$$\Delta\overline{I}_{+}^{s} = \overline{I}_{+}^{s} - \overline{I}_{+}^{s,pf} \simeq -\frac{1}{2}\overline{I}_{+}^{s,pf} + \frac{1}{6}\overline{I}_{fault}\,; \quad (9)$$

$$\overline{I}_{-}^{s} \simeq -\frac{1}{2}\overline{I}_{+}^{s,pf} + \frac{1}{6}\overline{I}_{fault} \quad (10)$$

$$\overline{I}_{0}^{s} \simeq \frac{1}{3}\overline{I}_{fault} \quad (11)$$

Near a MV/LV transformers the ratio between the fault and the load resistances may be small, and the following approximated expressions hold:

$$\overline{I}_{fault} \approx \frac{1}{3}\overline{I}_{+}^{s,pf}\,;\ \Delta\overline{I}_{+}^{s} \approx -\frac{4}{9}\overline{I}_{+}^{s,pf}\,;\ \Delta\overline{I}_{-}^{s} \simeq \Delta\overline{I}_{+}^{s}\,;$$

$$\Delta\overline{I}_{0}^{s} \approx -\frac{1}{9}\overline{I}_{+}^{s,pf}\,; \quad (12)$$

Of course, if on the contrary the fault resistance is much larger than the load impedance, expressions (9-11) degenerate into (5-7). Anyway, the values of both sets of expressions depend on the existence of a load before the conductor breaks. Without load, there is no change in the sequence currents as seen from the source side, and yet there is a real danger for human safety if somebody touches the broken conductor (see the companion paper [2]).

PROTECTION APPROACHES BASED ON STEADY-STATE SEQUENCE CURRENTS

Conventional protection approaches against broken conductors are based on steady-state currents, either zero or negative (hereafter named options I and II). For both approaches sensitivity is limited by the requirement to not trip for unbalance-driven currents, but for the negative current there is an additional commercial proposal in which the ratio of negative to positive sequence currents is employed to improve discrimination [3], as the next figure illustrates. Hereafter it will be named option II^{+}.

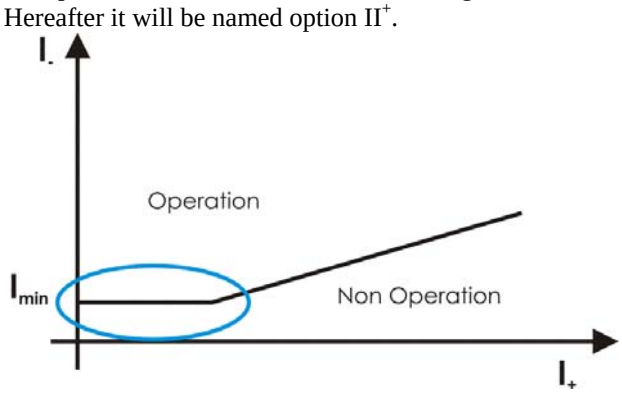

Figure 2: Negative current based approach to detect broken conductors constrained by the positive current.

To evaluate these three methods, a particular portuguese sub-transmission network was selected for which data is well defined.

Figure 3-top shows random samples of the negative current as seen form the source side of one of the target lines. Sequence currents were extracted from on-demand records. The maximum negative current almost reaches 6A, but unfortunately its ratio to the positive current is poor, as Fig. 3-bottom shows. Indeed, in distribution networks negative current comes more from unbalanced LV loads than from asymmetries in the parameters of the network, even though those asymmetries yields more impact on the negative than on the zero current.

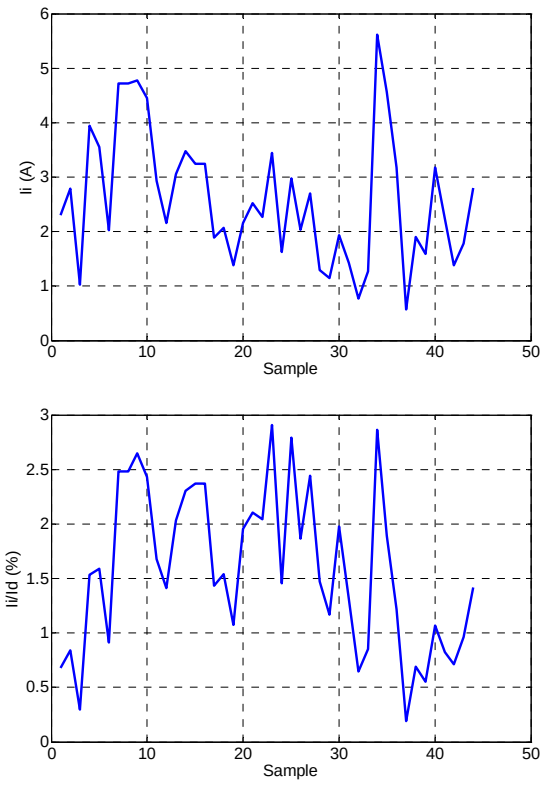

Figure 3: Record of the negative current as seen from the source side of a target line (top), and its relationship to the positive current (bottom).

To set the virtual relays, the following aspects were taken into account:

- The zero sequence relay (approach I) measures 3x $\overline{I}_0^s$ (residual current) and was set to detect 2A, to account for unbalance-driven zero current (which can reach up to 1 A) and typical measuring inaccuracies;
- The negative sequence relay (II) had to be made insensitive to negative currents resulting from unbalanced load with balanced voltage (up to 3%), plus balanced load fed by unbalanced voltage (which can reach 1%), and measuring inaccuracies. These include CT errors, which can not be replaced by a window-CT as for the zero current measurement. Since the maximum load current for the considered line was 400 A, a 30 A setting was defined.
- The improved negative sequence relay (II^+) can adapt its sensitivity to the load current, which supports a basic setting of 10A. However, for usual load currents the resulting adapted setting is not much smaller than the previous one.

Applying these settings on the targeted network, it can be easily shown that with the exception of resonant grounding, for any type-A condition (broken conductor connected by its receiving end), approach I (zero-current) is always more

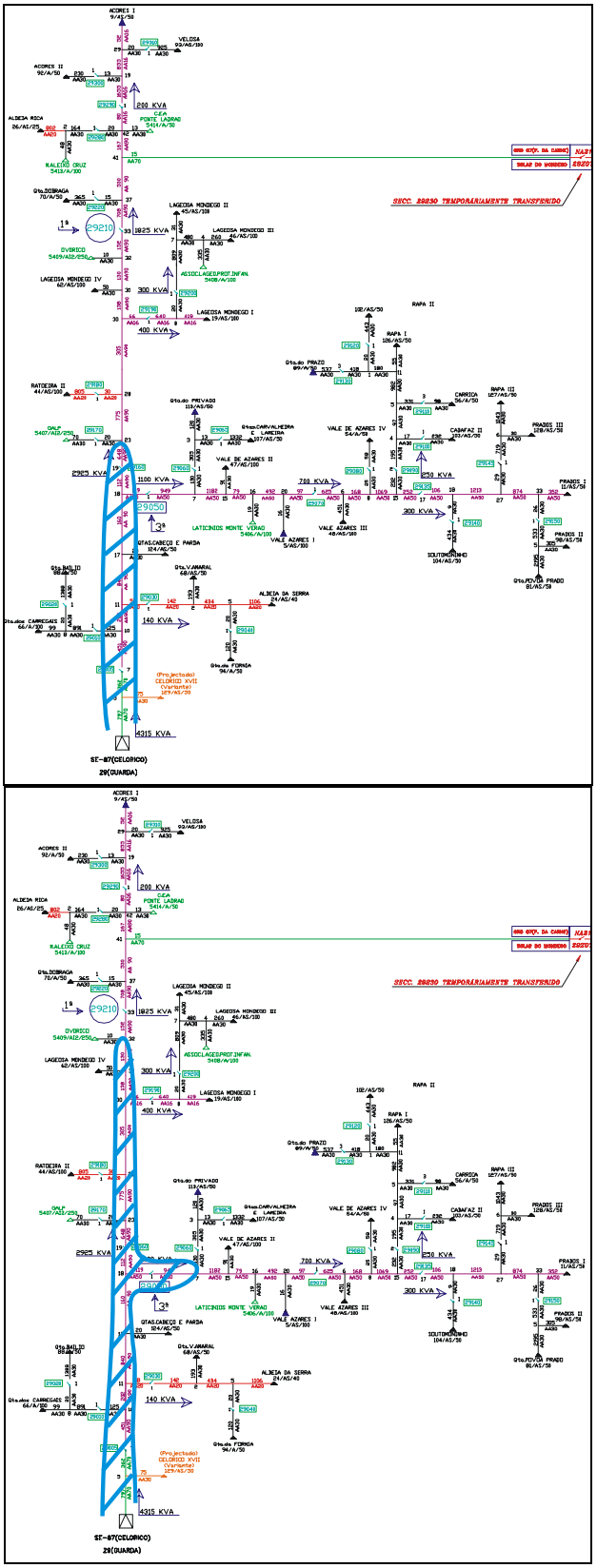

Figure 4: zones reached by approaches II (top) and II+ (bottom) for condition A. Approach I is ineffective.*

effective. For type-A^* condition (very high-resistance fault),

however, approach I is ineffective.

Figure 4 shows the reached zones for type-A* faults by approaches II and II+, which is better for II+, as it was expected. However, for type-B faults the zones reachable by approaches II and II+ are a little smaller, while the reach of approach I is better, as it is illustrated in Figure 5.

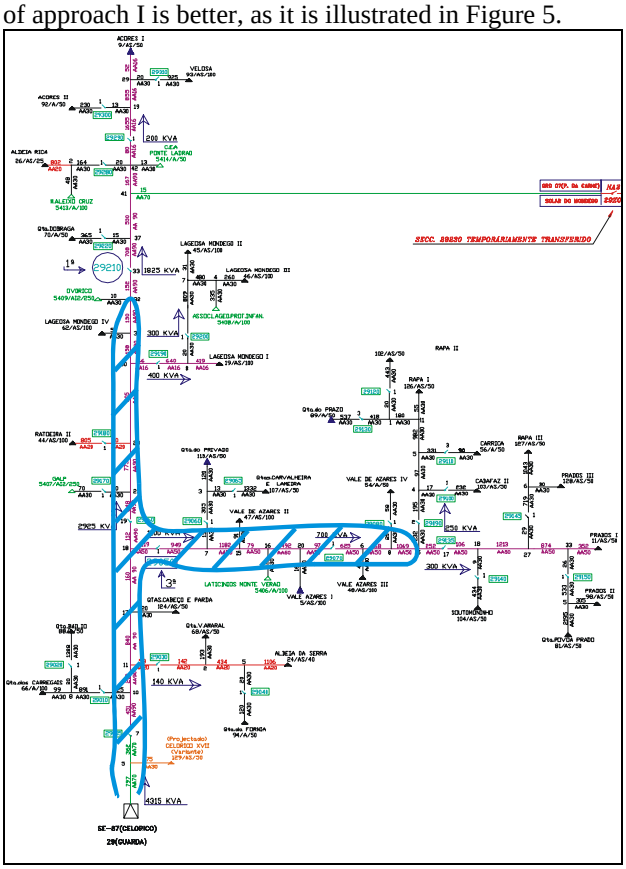

Figure 5: reached zone by approach I for type-B condition.

DISCUSSION

It must be underlined that both approaches II/II+, as well as approach I for type-B condition, depend on the existence of a meaningful load current before the conductor breaks. Distribution networks are usually radial from a substation bus, and secondary branches feeding small MV/LV transformers may carry very small load currents when they are compared to the main feeder rated current. Therefore, approach I is almost always better to detect broken conductors, unless they do not touch soil. However, even in this case negative-sequence based relaying is only effective near the substation bus, when load current is large and so it is the value of the negative current resulting from the fault. Actually, negative current-based protection is better suited to detect broken conductors in transmission lines, may be complementing distance relaying. So, it can be asserted that to improve the detection of fallen broken conductors in distribution networks, only approaches not depending on load current can offer hopeful solutions.

CONCLUSIONS

Both zero and negative sequence currents based relaying can detect sets of broken conductor conditions, but they have different capabilities and drawbacks. For receiving end connected conductors fallen on soil, zero sequence currents approach is usually better, while negative sequence current may be better for very-high resistance earths or conductors not in touch with soil. Broken conductors connected by their sending ends (load side) may be detected by both approaches, although as a rule zero sequence based approach will usually be more sensitive, particularly for faults near the loads. Anyway, for this type of fault and for all negative current based methods, effectiveness depends on the existence of a meaningful load current. Significant improvements regarding broken conductor detection in distribution networks can only be expected from new approaches not depending on load currents.

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[3] AREVA, 2001, “MICOM P14x Technical Manual”, 82-84