FAULT CLASSIFICATION FOR DISTANCE PROTECTION

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Abstract: This paper presents an overview of fault classification methods and challenges. It also contains some ideas about structured testing.

Keywords: distance protection, fault classification, phase selection.

1. INTRODUCTION

Suitable background information about computer relaying can be found in reference [1]. The purpose of distance protection is to trip for faults within the protected zone only. To achieve this goal the distance protection is often structured into the following critical algorithms [1], [2].

- Fault detection
- Fault classification
- Direction discrimination
- CT saturation detection
- Distance estimation

The term fault classification is often used synonymously to phase selection. To be strict, fault classification aims to determine the fault types, whereas phase selection aims to determine the faulted phases only. Therefore we make a distinction between fault classification and phase selection. For a single line there are 11 different types of shunt faults. Their IEC notations are: L1N, L2N, L3N, L1L2N, L2L3N, L3L1N, L1L2, L2L3, L3L1, L1L2L3, L1L2L3N. Phase selection is primarily used to enable single pole tripping and has 7 possible outputs, namely: L1, L2, L3, L1&L2, L2&L3, L3&L1, L1&L2&L3. A fault classification algorithm always gives unique information for phase selection, but the other way around is not always true.

Fault classification plays an important role for a distance protection relay. The algorithm shall, with a high degree of probability, classify all possible realistic fault-types in order to enable single pole tripping and auto-reclosing. Knowledge about the fault type can also be used to improve reach properties of impedance zones. The risk of unwanted overreach is reduced, if the classified fault type is used to select the impedance loops relevant to the actual fault type.

2. REVIEW

Several fault classification algorithms have been presented in papers and information can also be found in patents.

Many algorithms use change in current and voltage, often called delta quantities, or superimposed quantities, to classify faults. Reference [3] explains delta quantities and how to use them for fault classification. The short circuit system is split into a steady state circuit and a superimposed circuit. The superimposed circuit is analyzed to find fault classification rules. More examples of delta quantities are given in [5].

Another approach, described in [6], is to use fault-induced transients to identify the fault type. An attractive fault classification is to use the angle between negative sequence and zero sequence current components for fault classification, see [8]. This results in a sensitive classification without the need to subtracting pre-fault quantities.

Reference [4] proposes a Kalman filter for fault classification. Voltages are used as input to two different Kalman filters, one assuming a faulted and the other a healthy system. The idea is to look for voltage abnormalities to classify a faulted phase.

Recently it has been suggested that AI, Neural networks, pattern recognition, fuzzy logic and other learning algorithms that needs training, could be used for fault classification.

3. CHALLENGES

One great challenge is to make a fault classification algorithm that works for a wide range of operating conditions without using delta quantities, i.e., subtracting pre-fault values. It is straightforward to use delta quantities if the system goes from a well-defined pre-fault state into a faulted state. Often this is the case. However, there exist some cases when pre-fault and fault conditions are not well defined. One example is sequential tripping, were tripping of non-delayed zones can change the network configuration to such a degree that the pre-fault conditions might become irrelevant for a relay that trips on a delayed zone. Another example is evolving faults, were the system can go from healthy into a single-earth fault and then into a double-earth fault. Yet another example is gradually breakdown of a high impedance earth fault, for example a dry tree, were the resistance to earth gradually brakes down over a longer time period. For all these cases, it might be non-trivial to define the pre-fault conditions.

The effect of remote end current, sometimes called the semaphore effect, is a complicating factor. We use an example to illustrate the difficulties caused by the semaphore effect. Consider the simple system in Figure 1 consisting of one line and two sources with data as Appendix A.

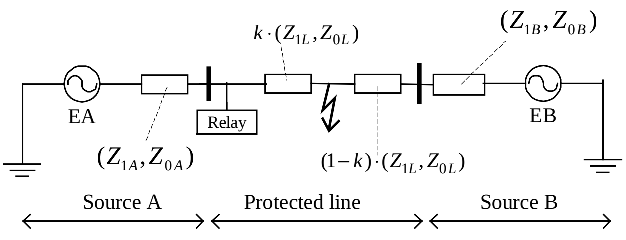

Figure 1. System with one line and two sources.

In the example we study an earth fault (L1N) with a total fault resistance (arc and tower foot resistance) of 10 ohm.

First we assume a fault at 5% of the line length. The time response for current and voltage is shown in Figure 2.

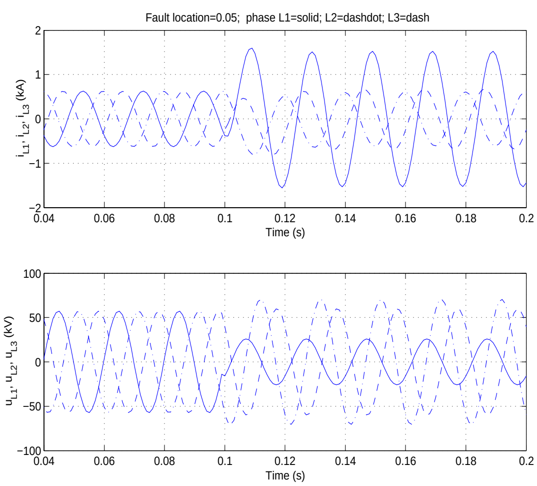

Figure 2. Time response for current and voltage for a L1N fault at 5 percent of the line length.

The phase-earth impedance is calculated as

$$Z_{L1N} = \frac{U_{L1N}}{I_{L1N} + K_N \cdot 3I_0} \quad \text{with} \quad K_N = \frac{Z_0 - Z_1}{3 \cdot Z_1}$$

where the current and voltage are calculated with a one-cycle DFT. The calculation of Z_{L2N} and Z_{L3N} are analogous. The result is shown in Figure 3.

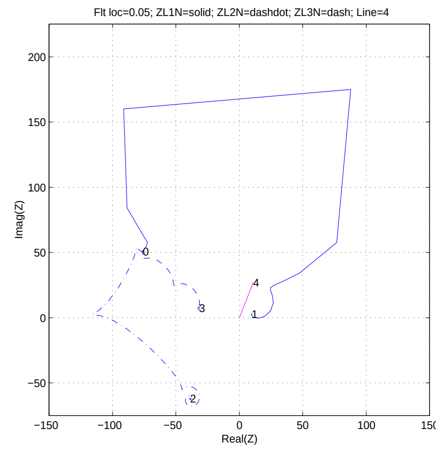

Figure 3. Phase-earth impedances for a L1N fault at 5 percent of the line length. Z_{L1N} =solid; Z_{L2N} =dashdot; Z_{L3N} =dash; Line impedance Z_{1L} =solid

Secondly we assume a fault at 95% of the line length. The time response for current and voltage is shown in Figure 4.

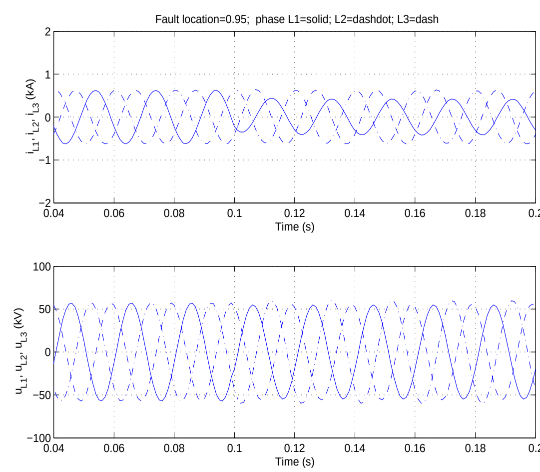

Figure 4. Time response for current and voltage for a L1N fault at 95 percent of the line length.

The phase-earth impedances are calculated and the result is shown in Figure 5.

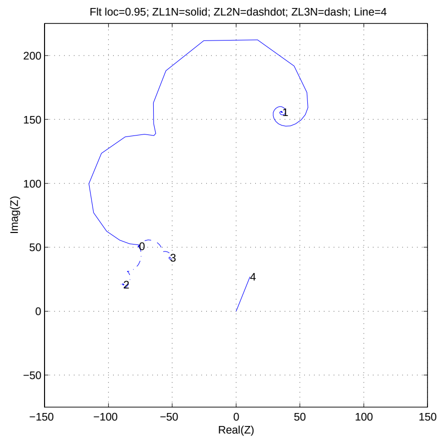

Figure 3. Phase-earth impedances for a L1N fault at 95 percent of the line length. Z_{L1N} *=solid;* Z_{L2N} *=dashdot;* Z_{L3N} *=dash; Line impedance* Z_{1L} *=solid*

From this simple example we note the following points.

- The current amplitude for phase L1 increase for a fault at 5% of the line length, but decrease for a fault at 95% of the line length.
- The impedance magnitude for Z_{L1N} decrease for a fault at 5% of the line length, but increase for a fault at 95% of the line length.
- An earth fault in phase L1, will also influence the impedance for Z_{L2N} and Z_{L3N}. This is due to the zero sequence current used in all phase-to-earth loops. If the zero sequence current is large, the influence is strong. This is illustrated by the fault at 5 % of the line length, which significantly decrease the impedance Z_{L3N}. This means that a forward fault could cause a zone 3 trip in reverse direction.

The reason for this apparently strange behaviour is the semaphore effect. For the fault at 95% at the line length, the remote end current is roughly 10 times larger than the current from the relay side. This magnifies the fault resistance seen from the relay, so it appears to be 10 times larger than the physical resistance of 10 ohm, i.e., it appears to be 100 ohm. The apparently large fault resistance, in combination with the pre-fault conditions of importing power, cause the unexpected behaviour of the current to decrease for the faulted phase.

Based on this simple example, we pursue that the following observations are relevant for fault classification.

1. It is not possible to use simple criterions only, such as current magnitude or impedance magnitude to determine fault type.
2. The semaphore effect can magnify and change angle of the physical fault impedance. The effect becomes very strong for faults close to the remote end, when the relay has a weak source, and the remote end source is strong. We can see that if source A is a weak station (Z_A>>Z_B) the apparent impedance will be enlarged significantly in the resistive direction. With a difference of phase angles between source impedances Z_A and Z_B , or source angles E_A and E_B, the fault resistance will also influence the reactive component of the apparent impedance. Understanding this is the key to good fault classification.
3. It is non-trivial to predict the combination of impedance values for the faulted system.

An awkward case is to classify simultaneous fault on different branches on a double circuit line. One solution is to use phase segregated communication between the two relay terminals.

4. Testing

The purpose of the testing during development is different compared to testing for a specific costumer application. Often development testing aims at finding out if an idea can be made into an algorithm that works for a broad range of systems and operation conditions.

One approach to efficient testing is to tailor made the testing at each stage in the development of a new algorithm. It is important to use the right tool in right stage of the algorithm development. All this might seem trivial and obvious. However, there are examples of extensive, and expensive, EMTP-simulation studies of “promising” phase selection algorithms, where simple steady state fault calculation should have proved the algorithm being poor.

4.1 Selection of test cases

The classic approach is to test the fault classification algorithms with a select number of cases that are believed to be the hardest. Important parameters are fault resistance, differences in source angles, source impedances, fault location, line data and voltage magnitudes. The idea is that algorithms that perform well under these benchmark tests will also perform well during practical operation in the power system. The problem is how to select these benchmark tests so they reflect all operation conditions and system configurations that exist in the real power system.

An alternative new approach is to specify a parameter range. Parameters for each test are randomly picked from this range. To make it hard for methods that use delta quantities, some test cases should involve sequential tripping, evolving faults and gradually breakdown of resistance to earth. A large number of tests are made. Each algorithm is scored by a failure rate, i.e., how many of the tested cases did the algorithm fail to classify.

Typical parameters to vary are

- Fault type
- Fault location
- Fault resistances
- System voltage and line impedance
- Line length
- Impedances for source A and source B
- Voltage magnitude and angle for source A and B

It is important to make an extra check if each combination of parameters is reasonable. The random selection can give unrealistic cases. A large source angle difference in combination with low impedances might result in too high currents. Also the semaphore effect can produce an apparent fault resistance that is unrealistically high.

For example, consider the system in Figure 1 with a physical fault resistance of 10 ohm and with a relatively weak source at the side A, such that $z_{0A} = 100 \cdot z_{0B}$ and $z_{1A} = 100 \cdot z_{1B}$. A fault close to the remote end will give an apparent fault resistance larger than 1000 ohm. It is unrealistic to demand that the fault classification should be able to classify this fault. A reasonable assumption is that the apparent fault impedance, including the semaphore effect, should always be less than the load impedance.

4.2 Stage 1 – Steady state testing

A first rudimentary test is made to sort out algorithms that do not even work at steady state condition. The purpose is to sort out algorithms with poor steady state performance. Typical tools are standard software packages like Matlab/Simulink [9], or fault calculation programs such as PSS/E [10]. Typically a large number of cases are tested, say 10 000 cases, where the system parameter, such as operation conditions, impedances, fault location and resistance are randomly chosen. The result is presented as a failure rate as

$$FR = \frac{n}{N}$$

where FR is the failure rate, n is the number of erroneously classified faults and N is the total number of tested cases. The failure rate can be used for a first ranking of different fault classification algorithms. An algorithm with too poor performance can be sorted out at this early stage and does not need any further testing.

4.3 Stage 2 – Dynamic simulation with simplified models

The second stage is to rank the different algorithms with respect to function time. A simplified dynamic simulation model is used to find the functional time and range for the different algorithms. Suitable tools are dynamic simulator with simplified models, typically two generators with internal impedances feeding one transmission line, with ideal voltage and ideal current transformers. A combination of selected cases, and cases with randomly selected parameter can be used. Typically some 1000 cases are simulated. The result is presented as algorithm function time for each case.

4.4 Stage 3 – Dynamic simulation with detailed models

The third stage is to do the final testing of the selected algorithm. Detailed models should be used to comply with different costumer specifications. Test data can also be taken from fault recorders. At this stage, it is suitable to use detail models for current transformers and capacitive voltage transformers [7]. It is also important to use an adequate line model with frequency dependent line parameters. Test specifications for major costumer can be used to create a large ensemble of realistic test cases. Typically some 100 cases are simulated.

5. Conclusions

This paper has presented an overview of fault classification methods and challenges. One complication factor is the semaphore that can magnify and change angle of the physical fault resistance. Reasonable specifications and structured testing is important for efficient evaluation of candidate algorithms.

6. References

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7. Appendix A – Data for two source system

Impedances are given at 50 Hz. Nominal voltage is 69 kV.

Line data: length 64 km; $z_{0L} = 0.36 + j1.44$; $z_{1L} = 0.17 + j0.42$ ohm/km.

Source A: $z_{0A} = 13 + j45$ ohm; $z_{1A} = 5 + j18$ ohm; $E_A = 1.1\angle 0^\circ$ p.u.

Source B: $z_{0B} = 1.5 + j5.0$ ohm; $z_{1B} = 0.2 + j2.0$ ohm; $E_B = 1.0\angle 30^\circ$ p.u.

Fault data: total fault resistance (arc and tower foot resistance) 10 ohm. Fault location either k=5%, or 95% of line length.

8. Biography

Magnus Akke (M’92) was born in Lund, Sweden 1961. He received his Master, Licentiate and Ph.D., all from Lund Institute of Technology, Sweden, in 1986, 1989 and 1997, respectively. He also has a Bachelors degree in Business Administration from Lund University, Sweden. For nine years he worked with power system analysis and relay protection at a major Swedish power utility. He has been a visiting scientist at University of Newcastle, Australia, and at Cornell University, USA. Since 1999 he works with development of new distance protection at ABB.