NEW DESIGN OF GROUND FAULT PROTECTION

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Abstract

Ground fault protection is widely used to protect transmission and distribution lines in case of ground faults. Combined with a directional element and used in a teleprotection scheme ground fault protection can detect and isolate even high resistive ground faults which are not seen by distance protection.
Today in general the directional element of ground fault protection is based on zero sequence components or negative sequence components. There is no clear advice which kind of polarization should be preferred for a special application. However there are a lot of maloperations due to incorrect result of the directional element of ground fault protection using either zero sequence or negative sequence quantities.
Analyzing numerous fault records it seems obvious that these problems with the directional elements cannot be solved using either zero sequence or negative sequence because these quantities are sometimes very small or not related to the fault.
One great advantage of numerical relays is that these relays measure all the voltages and currents of a three phase system. Analyzing fault records related to complicate cases for ground fault protection it can be seen that there is much more information about the fault than used by today's implementations of ground fault protection. For instance the location of the impedance in the complex plane often gives a clear indication about the direction to fault.
This paper suggests a new design of ground fault protection using this additional information given by the numerical relays. The starting condition for the ground fault protection remains a threshold of zero sequence current. Once this threshold is exceeded a multi-criteria phase selector selects the faulted phase. Several criteria based on magnitudes of voltages and currents, changes in voltages and currents, symmetrical components and impedances are applied in parallel. The results of each single criterion are weighted and combined to get a final result for the selection of the faulted phase.
Using the information of the faulted phase a multi-criteria directional element is suggested to estimate the direction to the fault. Different criteria based on actual voltages, memorized voltages, symmetrical components and delta quantities are applied in parallel. The final result is obtained by the multi-criteria directional element as a weighted combination of the result of each single criterion.
This paper explains the new algorithm in more detail and illustrates the advantages of the proposed method using some real fault records. With the new design the ground fault protection takes a lot of advantages regarding phase selection and directional element from the distance protection. The main difference between distance protection and ground fault protection remains the different grading. For distance protection the sensitivity is limited by the resistive reach. The basic principle for grading of ground fault protection remains a simple threshold of zero sequence current.

1 Introduction

In general for single-phase to ground faults the current of the faulted phase is increasing and the voltage of the faulted phase is decreasing.
Ground fault protection calculates the ground current 3I0 as criterion for pickup and grading:

$$3\underline{I}0 = \underline{I}A + \underline{I}B + \underline{I}C \qquad (1)$$

If the ground current 3I0 exceeds a certain threshold, the ground fault protection will generate a pickup signal. In case of directional ground fault protection the direction to fault needs to be calculated to validate the trip command.
Electromechanical relays uses zero sequence voltage or zero sequence current of transformer star point to calculate the direction to fault. These quantities were easy to obtain and valid for all types of fault.
Later polarizing with negative sequence quantities was applied because negative sequence is more immune against mutual coupling of parallel lines. However even polarizing with negative sequence is not a perfect solution.
In chapter 2 three different cases of incorrect operation of directional ground fault protection are explained. Chapter 3 introduces a new idea for the phase selection of the ground fault protection using more information about the fault which is available in a multifunctional relay. Chapter 4 explains a new idea of a directional element for ground fault protection based on the combination of different criteria used in distance protection.

2 Real-world cases of incorrect operation of directional ground relays

In the following subchapters three cases of incorrect operation of directional ground fault protection are explained in detail.

2.1 Case 1: Wrong trip using zero sequence polarization

The first case presents a wrong trip of directional ground fault protection on a 147 km line, 132 kV in Malaysia. Figure 1 shows the impedance trajectories in the complex plane. It can be seen that the fault was BG, far away from the polygons of distance protection in reverse direction.

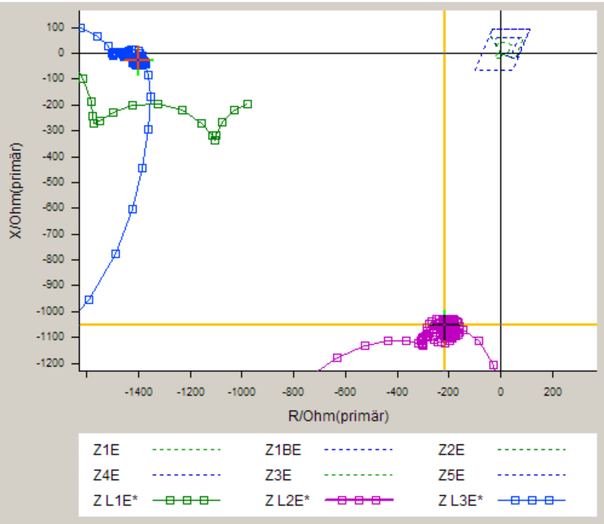

Figure 1: Impedance trajectory for the BG fault

Figure 2 shows the currents and voltages for the BG fault and the related binary signals.

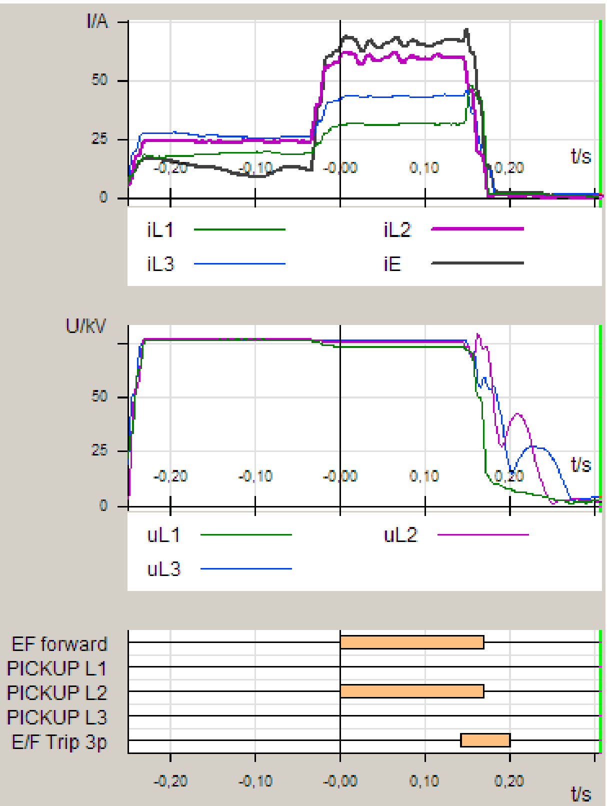

Figure 2: Voltages, currents and binary signals of BG fault

The ground current iE exceeds the sensitive threshold of 50A primary which leads to a pickup of the ground fault protection. The current of phase B is raising most which is consistent with the pickup of phase B.

The changes of voltages after fault inception are not very big but leaving enough quantity of zero sequence voltage and negative sequence voltage for the directional element.

Figure 3 is showing the zero sequence quantities and negative sequence quantities in the phasor diagram. It can be seen that the zero sequence current is leading the zero sequence voltage by approximately 100° which is a clear indication for a fault in forward direction. The negative sequence current however is lagging the negative sequence voltage by approximately 60° which is a clear indication for a fault in reverse direction.

In this case zero sequence quantities are a little larger than negative sequence quantities. That’s why zero sequence is chosen as directional element which leads to the wrong trip of the directional ground fault protection in this case.

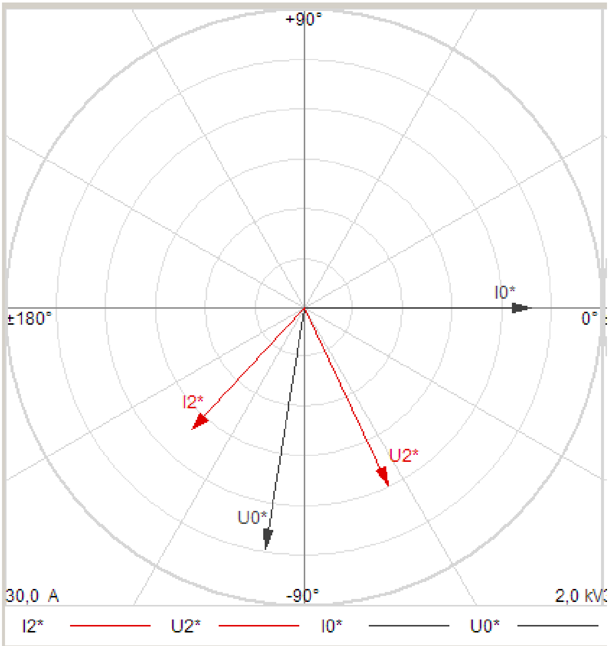

Figure 3: Zero sequence and negative sequence quantities in the phasor diagram

The reason why zero sequence and negative sequence show a different direction in this case is not known by the author. From the theory of a single phase to ground fault zero sequence and negative sequence should give the same result. In practical applications however there are a lot of reasons influencing the directional elements based on zero sequence or negative sequence [1].

Using additional information like the impedance trajectory shown in Figure 1 could help to improve the directional element of ground fault protection.

2.2 Case 2: Wrong polarization due to an error of voltage transformer

In [3] a wrong trip of ground fault directional relay for an AG fault in reverse direction was reported which was caused by an error of a related voltage transformer. Figure 4 shows the impedance trajectories in the complex plane. It can be seen that the fault AG appears in reverse direction.

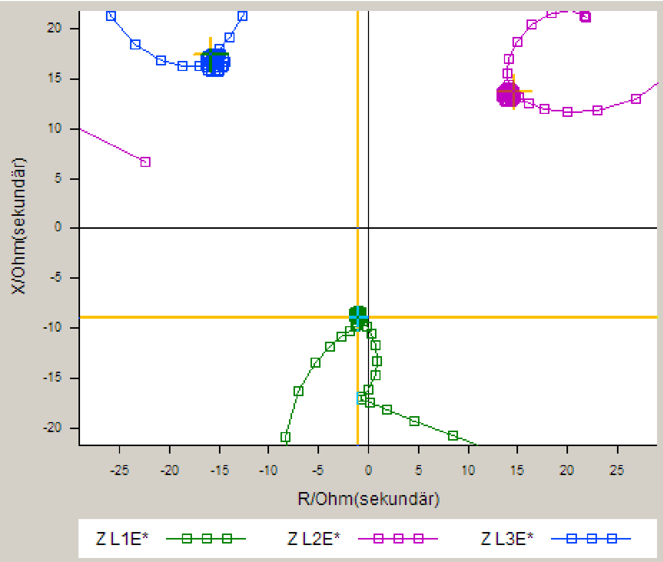

Figure 4: Impedance trajectory for the AG fault

Figure 5 shows the currents and voltages for the AG fault and the related binary signals.

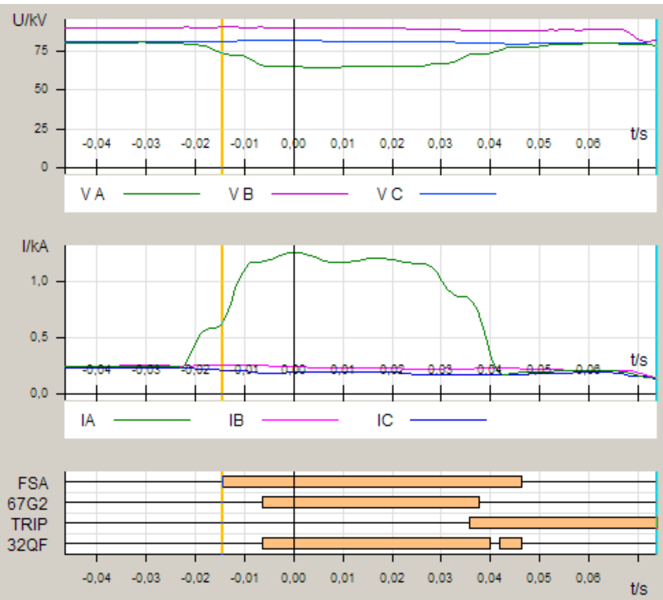

Figure 5: Voltages, currents and binary signals of AG fault

There is a significant decrease in the voltage of phase A which is a clear indication for a fault A to ground. The voltage of phase B shows an asymmetry due to an error of the voltage transformer. This wrong reading of phase B voltage has a major impact on the wrong direction determination using negative sequences quantities.

The current of phase A is raising most which leads to a pickup of ground fault protection indicated by the signal “67G2”.

The signal “FSA” indicates that the relay detects the faulted phase but unfortunately it detects the wrong direction indicated by the signal “32QF”.

The reason for the wrong decision of the directional element is shown in Figure 6 presenting the zero sequence quantities and negative sequence quantities in the phasor diagram. It can be seen that the negative sequence current is leading the negative sequence voltage by approximately 160° which is a clear indication for a fault in forward direction. The zero sequence current however is lagging the zero sequence voltage by approximately 100° which is a clear indication for a fault in reverse direction.

In this case the negative sequence quantities were chosen by setting to detect the direction to fault. This leads to the wrong trip of the directional ground fault protection in this case.

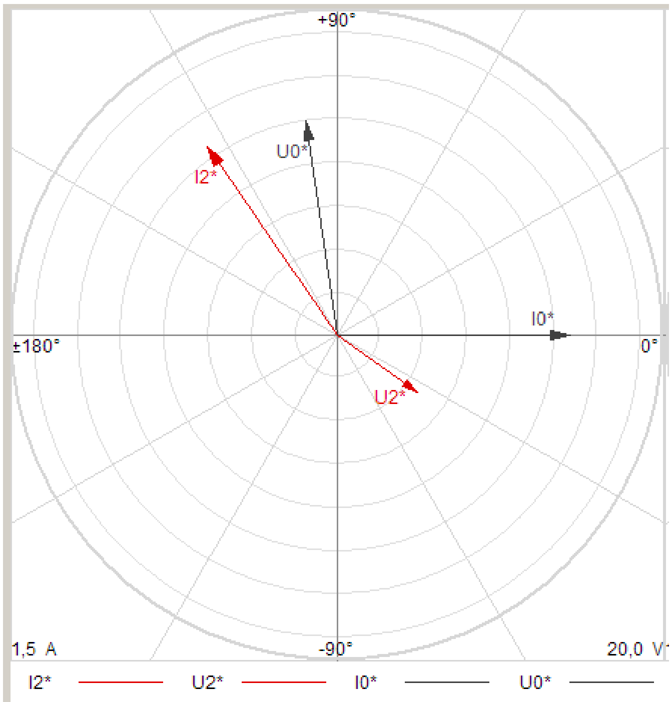

Figure 6: Zero sequence and negative sequence quantities in the phasor diagram

In [3] it was mentioned, that the fault locator included in the same relay which was tripping for a ground fault in forward direction using the function 67N reported a fault AG in reverse direction.

The question was raised why the directional element of the function 67N does not use the information available for the fault locator.

2.3 Case 3: Wrong phase selection

At ISA REP a test was conducted using a test system shown in Figure 7.

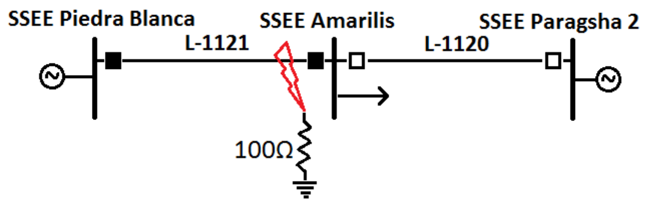

Figure 7: Test configuration at ISA REP

A single phase high resistive fault BG was applied very close to Amarilis substation. At this time the line L-1120 was out of service. Due to this Amarilis was a weak infeed side with a transformer with a delta winding on its 10 kV side.
Figure 8 shows the impedance trajectories in the complex plane. The applied fault BG appears on the real axis of the complex plane in forward direction.

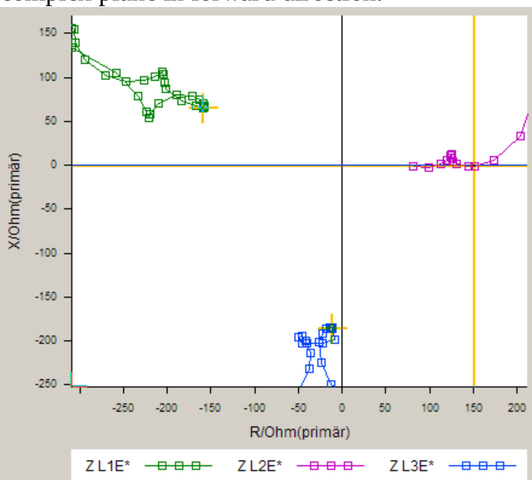

Figure 8: Impedance trajectory for the BG fault

Figure 9 shows the currents and voltages for the BG fault and the related binary signals.

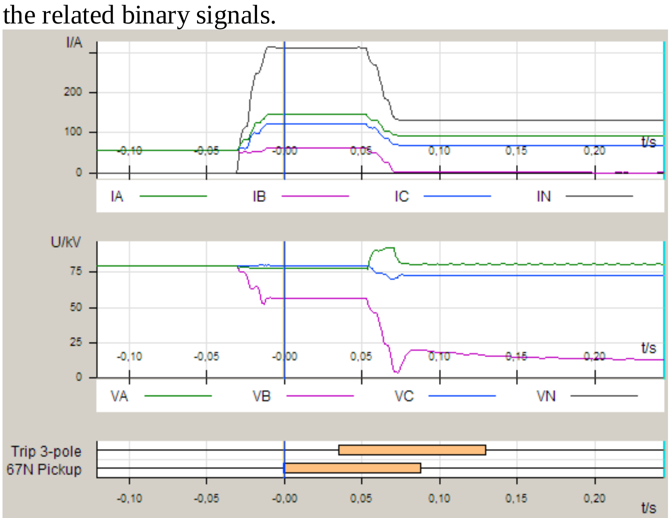

Figure 9: Voltages, currents and binary signals of BG fault

Due to the transformer on the weak side all three phase currents are nearly in phase, producing a ground current which is much bigger than each single phase current.
This ground current causes a pickup of the ground fault protection indicated by the signal “67N Pickup”.
Even if there is a significant decrease in the voltage of the faulted phase the ground fault detection was not able to detect the faulted phase. Instead of a single pole trip command for phase B a three pole trip was issued indicated by the signal “Trip 3-pole”.
The reason for this unselective trip was the method applied to detect the faulted phase for a single phase to ground fault. This method is based on the relation between the angle of negative sequence current and the angle of zero sequence current like shown in Figure 10.

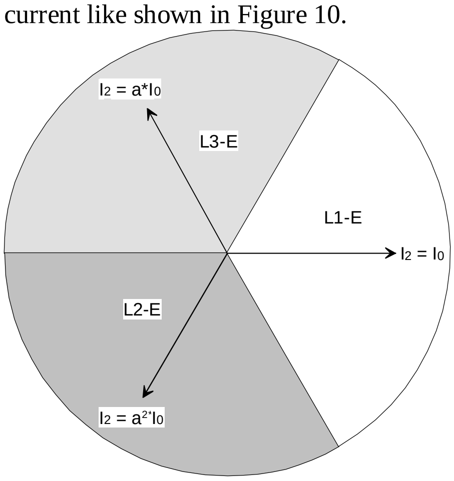

Figure 10: Basic principle of phase selection

According to this principle zero sequence current should lead the negative sequence current by approximately 120° for a fault BG.
As shown in Figure 11 the zero sequence current is leading the negative sequence current by approximately 60° only which is no clear indication for any type of fault. In addition to this it must be stated, that the magnitude of the negative sequence current is very small compared to the magnitude of the zero sequence current.

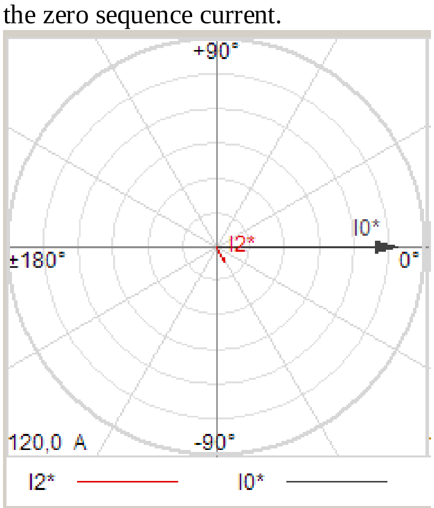

Figure 11: Negative sequence current in relation to zero sequence current for the BG fault

3 Multi-criteria phase selection

If there is a pickup of ground fault protection due to ground current exceeds the threshold the next step should be to find out the faulted phase. This is important to be able to issue a single pole trip in case of a single phase to ground fault. It is also important to know the faulted phase to improve the directional element of ground fault protection which is explained in the next chapter.
Today the basic principle of phase selection for ground fault protection is based on the relation between the angle of negative sequence current and the angle of zero sequence current like shown in Figure 10.
In a modern multifunctional digital relay there is much more information about the faulted phase which could be used by the ground fault protection. The suggestion is to apply at least parts of the faulted phase selection used by distance protection for the phase selection in ground fault protection.
In [3] an example is given for a multi-criteria loop selector for the distance protection.
Figure 12 explains the principle of the multi-criteria phase selector for the ground fault protection. Several criteria for phase selection are applied in parallel. Each criterion gives a certain quality for each phase to be the faulted phase. Additional to this each criterion can be weighted according to its importance for the decision about the faulted phase.
Finally there is a weighted sum of quality for each phase to be the faulted phase. The faulted phase is chosen to be the one with the highest quality exceeding a dynamic threshold.

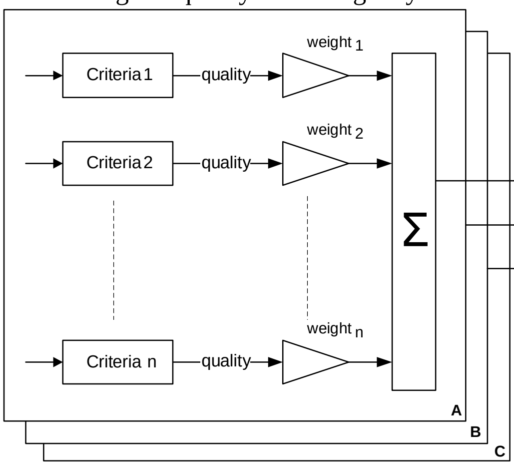

Figure 12: Calculation of phase quality

The following criteria could be applied to get the faulted phase for ground fault protection:

- Phase current
- Delta current
- Current sample
- Current phasor
- Phase voltage
- Delta voltage
- Voltage sample
- Voltage phasor
- Impedance
- Symmetrical components

Figure 13 gives an example of the output quality of the voltage criterion. A strong voltage drop in case of a fault results in a high quality of the voltage criterion for the related phase. If the voltage drop is only marginal the quality of the voltage criterion of the related phase will have a low quality.

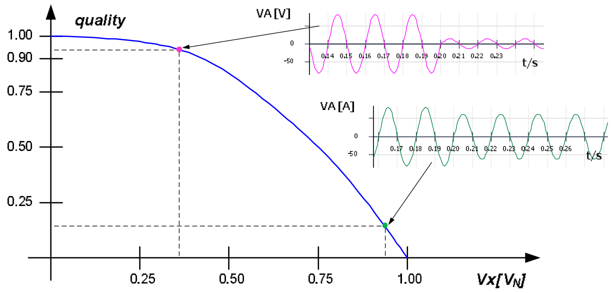

Figure 13: Quality of voltage criterion

Figure 14 illustrates the output quality of the impedance criterion. If the measured impedance of a phase to ground loop is close to the origin the quality of the phase to be the faulted phase is high. If the impedance is measured far away or has an angle which is not typical for a faulted loop the quality of the impedance criteria is low.

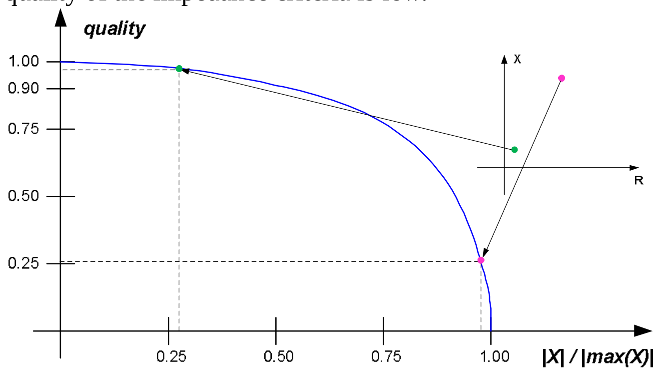

Figure 14: Quality of impedance criterion

Related to case 3 explained in chapter 2.3 the criteria for phase selection would work as follow:
The voltage criterion would give a high quality for the faulted phase B. This is because as seen in Figure 9 the voltage of phase B is decreasing and the voltages of the unfaulted phases do not change.
Also the impedance criterion would give a high quality for the faulted phase B. This is because as shown in Figure 8 the loop BG has the impedance with the smallest reactance showing a high fault resistance only.
The criterion based on symmetrical components gives a low quality for all phases. According to Figure 11 the angle of negative sequence current related to the angle of zero sequence current is on the border between two sections shown in Figure 10. Additional to this the magnitude of negative sequence current is very small compared to the magnitude of zero sequence current which limits the quality of this criterion.
Finally using a weighted sum of different criteria according to Figure 12 the right faulted phase for case 3 can be selected using the concept of multi-criteria loop selector.

4 Multi-criteria directional element

Today the directional element of ground fault protection is based on zero sequence quantities or negative sequence quantities. Different manufacturers offer different characteristics and different recommendations how to use these elements.
The IEEE PSRC report “Considerations in Choosing Directional Polarizing Methods for Ground Overcurrent Elements in Line Protection Applications” [1] explains known problems with the polarization but is not able to give recommendations for all use cases. Numerous use cases are marked with “Study required” or “OK, but study recommended”.
The idea of this paper is to overcome these problems of directional element for ground fault protection by using a multi-criteria directional element applying a structure as shown in Figure 15.

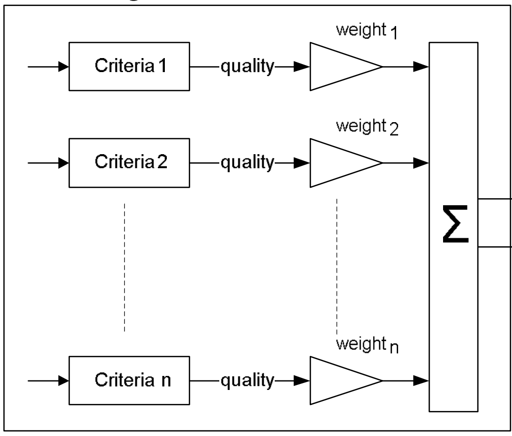

Figure 15: Structure of multi-criteria directional element

Using the information about the faulted phase additional criteria can be used to determine the direction to fault.
Finally the following criteria can be used for the directional element of ground fault protection:

- Zero sequence polarization
- Negative sequence polarization
- Self polarization (Current and voltage of the faulted phase)
- Memory polarization (Current and memory voltage of faulted phase)
- Cross polarization (Current of faulted phase and actual voltage of unfaulted phase)
- Memory cross polarization (Current of faulted phase and memory voltage of unfaulted phase)
- Polarization using delta quantities of faulted phase
- Polarization using delta quantities of symmetrical components

Figure 16 shows the result of the multi-criteria directional element applied to the fault case 2 explained in chapter 2.2. The binaries show that 7 criteria determine the fault in reverse direction. This results in a quality of 75% for the determination of the right direction.

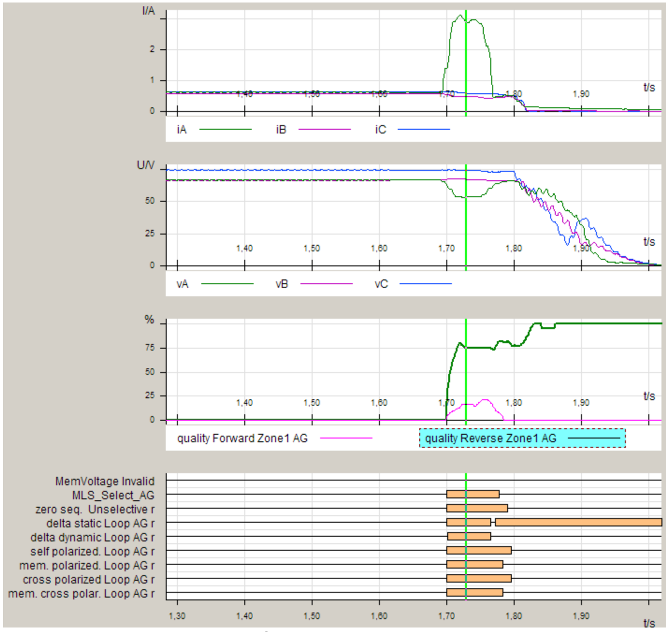

Figure 16: Results of multi-criteria directional element applied to case 2

Acknowledgements

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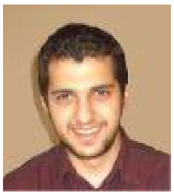
7 Biographies

Jörg Blumschein studied technical cybernetics and process measurement at the University Magdeburg where he became a graduated engineer in 1992. Since 1992 he works with SIEMENS in the development department of protection relays. Today he is the Principal Key Expert for Protection.



Yilmaz Yelgin studied computer science at the technical university in Berlin and graduated in 2004. Since 2006 he works with Siemens in the development department of protection relays. His main field of activity is the analysis of reasons and effects of power swing.