A NEW DIRECTIONAL TRANSIENT RELAY FOR HIGH OHMIC EARTH FAULTS

Gernot DRUML
A. Eberle GmbH - Germany
g.druml@ieee.org

Andreas KUGI
Saarland University - Germany
andreas.kugi@lsr.uni-saarland.de

Olaf SEIFERT
Dresden University of Technology
seifert@ieeh.et.tu-dresden.de

ABSTRACT

Statistics show that earth faults constitute a large portion of grid faults. Conventional relays are designed only for low ohmic earth faults under stationary conditions. They cannot handle high ohmic earth faults, which occur especially in rural networks with overhead lines, or intermittent earth faults in compensated cable networks. As a consequence the earth fault is very often not recognized or the wrong feeder is selected to be healthy. This increases tremendously the time for the localization of the earth fault. On the other side the effective protection of the networks became more and more important in the competitive markets.

In this paper, a new algorithm for detecting also high ohmic earth faults up to some kOhm and its benefits are explained in detail. Results from field tests to demonstrate the feasibility of this new method are presented.

INTRODUCTION

In many countries of the EC the "resonant grounding" is one of the most important options in electrical network design to obtain the optimal power supply quality. The main advantage of the treatment of the neutral point is the possibility of continuing the network operation during a sustained earth fault. As a consequence this reduces the number of interruptions of the power supply for the customer [1]

With this, new power quality problems arise for the selective detection of earth faults. The conventional relays are only designed for low ohmic earth faults.

Up to now, the advantage of transient relays lies in the fact that they are working almost perfect for very low ohmic earth faults with a fault-resistance less than a few ohms, independent of the type of the neutral grounding method.

With the new algorithm a directional earth fault detection up to some kOhm is possible and it is independent of the ignition point of the arc respectively the starting point of the high ohmic earth fault.

At present the fields of application being preferred for transient relays in the medium voltage were cable networks. With the new algorithm the relay is also applicable for rural networks, where the probability of a high ohmic earth fault is much higher.

The algorithm can also be used for the detection of restriking earth faults in compensated cable networks and intermittent earth faults in isolated networks.

The algorithm was extensively tested with various simulation models in Matlab/Simulink/SimPowerSystems before it was implemented into the real relay.

BASICS OF THE EARTH FAULT

To explain the behavior of a single pole earth fault, three different processes can be superposed [2], [3]. All three processes are starting at the same time, but their duration is different.

It can be distinguished between the following processes:
- discharge of the faulty line over the earth
- charging of the two healthy lines over the earth
- stationary state of the earth fault

The explanation of the three processes will be made by using a network with three feeders (A, B and C) and an earth fault in line 1 of feeder A according to figure 1.

Fig.1: Discharge of the faulty line over the earth

Discharge of the faulty line over the earth

The lines can be considered as a distributed lattice network, consisting of a complex serial impedance $Z_{AX}$ and a line-to-
The greatest probability for the first ignition is near the maximum of the line-to-ground voltage \( V_{IG} \). At this time the line has about the maximum charge. The discharge of the lattice network of line 1 will start at the fault location and will propagate as a wave in both directions to the ends of line 1. The supply-transformer as well as the distribution transformers at the loads can be considered as high-ohmic terminations of the line. The extension of the propagation of the wave to the two healthy feeders is blocked. Also the influence of an existing Petersen-Coil is blocked. Moreover, a reflection of the waves occurs at the end of the line respectively at every change of the image impedance of the line, for example at the substation or at a splitting point from one line in two ore more lines. These reflections can be detected in form of oscillations at a high frequency in the zero-sequence current and in the zero-sequence voltage. 

Important parameters for the behavior of the discharge are:
- Capacity of line 1 to ground
- Charge of the line-to-ground capacity before the start of the first ignition
- Serial line impedance \( Z_L \) of line 1 in the faulty feeder and in the healthy feeders
- Impedance \( Z_F \) at the fault location, including the grounding resistance

The lines of phase 1 of the healthy feeders can be considered as a parallel connection of these lines, which results in a lower impedance of the equivalent serial impedance and a higher equivalent line-to-ground capacity of the healthy feeders. The oscillation frequency essentially depends on the serial impedance and the line-to-ground capacity which are, in a first approximation, proportional to the length of the line.

The frequency is higher for short networks and is lower for large networks. Usually, the oscillation-frequency is above 10 kHz.

**Charge of the two healthy lines over the earth**

As a result of the discharge of the faulty line the triangle of the voltages is destroyed and the voltage \( V_{IG} \) is more or less zero (fig. 2.b).

In fig. 3 the charging process for the network with three feeders is shown in detail.

![Fig 3: Charging of the two healthy lines over the earth](image_url)

Important parameters for the behavior of the charging are:
- Capacity of line 2 and line 3 to the ground
- Charge of the line-to-ground capacities before the start of the first ignition
- Charge voltage \( V_{21} \) and \( V_{31} \)
- Leakage inductance of the supply transformer
- Serial line impedance \( Z_L \) of the lines
- Impedance \( Z_F \) at the fault location, including the grounding resistance

The distribution transformers respectively the loads are comparatively high ohmic and can be neglected in the first approximation. The resistive load results in an additional damping of the charge oscillations. If the distribution transformer has no load on the secondary side only the very high ohmic magnetizing inductance takes effect.

The essential remaining inductive components for the description of the charge oscillations are the relative low ohmic leakage inductance of the supply transformer and, for earth faults which are far away, the inductance from the point of the supply transformer to the fault location.

The influence of the Petersen-Coil can be ignored, as the impedance of the Petersen-Coil is much higher than the leakage inductance of the transformer.
For the charging process of the two healthy lines the following equivalent circuit (fig. 4) can be used.

\[ L_{eq} = 1.5 L_{Tr}, \]
\[ C_{eq} = 2 C_{2E}. \]

![Equivalent circuit for the charging of the two healthy feeders](image)

For low ohmic earth faults \((Z_F <<)\) the frequency of the charge oscillations can be approximated by equation (1).

\[ f_c = \frac{1}{2\pi} \sqrt{\frac{1}{L_{eq} C_{eq}}} = \frac{1}{2\pi} \sqrt{\frac{1}{L_{Tr} C_{2E}}} \]  \hspace{1cm} (1)

Equation (1) can also be used, if the inductivity of the line from the substation to the fault location is taken into account, by adding it to the leakage inductivity of the supply transformer. As a result, the frequency of the charging oscillations is reduced. Thus, from equation (1) we may draw the conclusion that the frequency of the charging oscillations is lower for an earth fault far away from the substation compared to an earth fault near the substation. Usually, the oscillation-frequency \(f_c\) is in the range from some 100 Hz up to some kHz.

From Fig. 3 the following conclusion can be made:

1) Two capacitive charging currents flow into a healthy feeder. These charging currents can be measured as zero-sequence currents. The amount of this zero-sequence current is proportional to the line-to-ground capacity of this feeder.

2) All the capacitive charging currents of the healthy feeders (B and C) have to flow over the fault location.

3) The charging currents of the faulty feeder (A) flow over the fault location and back to the supplying transformer in line 1. As a result, these currents cannot be measured in the zero-sequence system. The sum of these four currents is zero.

4) The zero-sequence current of the faulty feeder is the sum of all charging currents of the healthy feeders but with inverse direction. Instead of a capacitive charging current there is an "inductive" charging current.

5) In a compensated network a superposition of the current through the Petersen-Coil takes place. The effect of this current is small at the beginning of the ignition.

As a conclusion the relay in the faulty feeder can only measure the sum of the charging currents of the healthy network in its back and that this current has an inverse direction.

**Stationary state of the earth fault**

For the explanation of the stationary state also Fig. 3 can be used. For an isolated network the whole capacitive current of all feeders flows over the fault location. The relays of the healthy feeders measure a capacitive zero-sequence current and the relay in the faulty feeder measures an inductive zero-sequence-current. In the stationary state, the size of this inductive current is, like in the previous section, the sum of the currents in the healthy lines in the back of the relay.

For compensated networks the situation is changed. In this case, the current through the Petersen-Coil superposes and reduces the capacitive current over the fault location [4]. In a well tuned network the capacitive current over the fault location is completely compensated. From Fig. 3 it can be seen that in this case the relay in the faulty feeder measures also a capacitive zero-sequence current, as well as the relays in the healthy feeders. Therefore, in compensated networks the inductive character of the zero-sequence current is no longer an indication of a faulty line.

Using a Petersen-Coil, the current over the fault location can be reduced to the small watt metric part, which is usually in the range of 2 % to 3 % of the whole capacitive line-to-ground current of the network.

**Superposition**

With the first ignition all three processes start at the same time.

In the next figures two different earth faults are shown for a 20 kV compensated network with three feeders and a capacitive current of 108 A and 5 A over-compensation. The network corresponds to the one of Fig. 3. The low-ohmic earth fault has a value of 10 Ohm and the high ohmic fault a value of 2000 Ohm. The sampling frequency of the recording is 10 kHz.

In the case of the low ohmic earth fault the high frequency oscillation of the discharging is higher.

In case of the high ohmic earth fault the zero-sequence voltage approaches about 40% in the steady state.

![Two healthy feeders at a low ohmic earth fault](image)
The conventional relays use the charging process to make the direction decision of the fault location. If the amount of the zero-sequence voltage $u_0$ exceeds a preset trigger level, a small window is opened for the measurement of the zero-sequence current $i_0$. The direction decision depends on the comparison of the sign of $i_0$ with the sign of $u_0$ during this measurement window. The fault lies in the direction of the feeder if the sign of $i_0$ is not equal to the sign of $u_0$. If the signs are identical, the fault lies in the direction of the bus-bar.

From Fig. 5 to Fig. 7 it is recognizable that, depending on the selection of the trigger level and the resulting measurement window, there are some possibilities for the relay to make a wrong decision of the earth fault direction. The trigger level for the zero-sequence voltage $u_0$ is usually set somewhere between 20% and 30%.

In the Section "Discharge of the faulty line over the earth" the ignition was discussed for the most probable situation at the maximum of the voltage $v_{1G}$. In the worst case, with an ignition at $v_{1G} = 0$, there will be no discharge oscillations and the high frequency of the discharge process cannot lead to an overshoot of the zero-sequence current.

However, there is still a charging oscillation, which can be used from the transient relay. Also in this case a wrong decision of the fault direction can be made, if the trigger level is near to the maximum of the zero-sequence voltage $u_0$.

Considering Fig. 7 it can be seen that in the case of a high ohmic earth fault the zero-sequence voltage is increasing slowly and that the zero-sequence current is more or less stationary at the point of trigger respectively during the measurement-window. In a well tuned compensated network the zero-sequence current $i_0$ is capacitive also in the faulty feeder, which leads to a wrong direction decision with high probability.

**New Transient Relay**

To avoid the disadvantages of conventional transient relays a new algorithm was developed. In the Section "Charge of the two healthy lines over the earth" it was shown that the two healthy lines were charged to the line-to-line voltage by the earth fault. This charging can be seen in the zero-sequence system.

The following considerations are based on the transient definition of the zero-sequence-system according to the space-vector-theory [5].

For example, for the healthy feeder B of our sample-network Fig. 3 the charging can be described with equation (2):

$$u_0(t) = u_0(t_0) + \frac{1}{C_{eqB}} \int_{t_0}^{t} i_{0B}(\tau) \, d\tau$$

(2)

Now $t_0$ can be chosen that $u_0(t_0) = 0$.

The new digital relays use signal processors having enough memory for large ring buffers and a sampling rate of 10 kHz or higher. These features enable the relay to use even past measurement data for the calculation.

Depending on the situation, it is possible to go back to one of the zero-crossings of $u_0$ in the past and to start the integration of the zero-sequence current $i_0$ from this chosen point up to the actual trigger point. The result of the integration shows that the curve of the integral of $i_0$ differs from the curve of $u_0$ only by the factor $C_{eqB}$, which is the equivalent zero-sequence capacitance of the feeder B. The integration of $i_0$ represents the actual charge $q_0$ on the feeder.

Drawing an diagram of this relation, with the integral of $i_0$ on the ordinate and the zero-sequence voltage $u_0$ on the abscissa results in a straight line with the gradient $C_{eqB}$. Subsequently, this diagram will be referred to as qu-diagram.

In the case of a faulty feeder this relation is no more valid. The sum of the charging currents of all healthy feeders flows out of the faulty feeder. The result of the integration of the zero-sequence current $i_0$ is no longer proportional to the zero-sequence voltage.

This behavior is shown in Fig. 8 for the two healthy feeders B and C and the faulty feeder A.
The integration of $i_0$ over a larger range makes it possible to detect also high ohmic earth faults up to some kOhm. In this case the integration has to start at a zero-crossing of $u_0$ some periods in the past.

Fig 8: qu-diagram of a low ohmic earth fault

Fig. 9 shows the qu-diagram for an earth fault with a fault impedance of 2000 Ohm. The corresponding time diagram of $i_0$ and $u_0$ is shown in Fig 7.

Therefore, the task for detecting a transient earth fault can be solved by the decision whether the curve in the qu-diagram is a straight line or not. It should be noticed that on-line versions of the least squares algorithm [6] and pattern recognition algorithms (e.g., [7], [8]) are implemented in the relay in order to improve the computational efficiency.

**New Transient Relay with restriking earth faults**

In the case of restriking earth faults, which very often occur in cable-networks, two new problems arise for conventional relays:
- The zero-sequence voltage $u_0$ does not always fall below the preset trigger level
- The zero-sequence current does not have a steady state

The first item is a problem for transient relays because they will not be retriggered.

The second item is a problem in particular for relays working on symmetrical components. Most of these relays are using the FFT to calculate the components of the fundamental frequency. During the decaying phase of $u_0$ the frequency of $u_0$ is changing, depending on the tuning of the Petersen-Coil. Both, the decaying and the restriking current have an influence on the calculation of the fundamental components. The result of this is, with high probability, a complete erroneous decision of the fault direction. This problem does not only occur in the faulty feeder, but even in the healthy ones. Fig. 10 shows that $u_0$ does not fall below the trigger value. The restriking starts above the preset value of 25%. In addition it should be noticed that the zero sequence current is not zero during the "healthy time" of the faulty feeder.

For a correct calculation of the fault direction the direction of the change of $u_0$ compared to the direction of the change of $i_0$ should be used. Conventional relays do not use this method.

Fig 10: Faulty feeder at a restriking earth fault

Fig 11: Healthy feeders at a restriking earth fault

Fig 12: qu-diagram of a restriking fault
Figure 12 shows the associated qu-diagram for the restriking fault.

This new algorithm enables the direction decision of the faulty feeder in an easy way. Only the qu-diagram of feeder A does not result in a straight line.

In the new relay the feeders are continuously supervised for a restriking earth fault if $u_0$ exceeds the preset trigger level. Also other methods based on the FFT (i.e. harmonics, wattmetric etc.) are implemented in the relay. These methods would lead to wrong results during the restriking earth fault. Therefore, the results of the other methods are blocked by the qu-algorithm during the restriking earth fault.

RESULTS OF FIELD TESTS

In the meantime the new algorithm is implemented in real hardware and has been proven to be feasible in real network configurations. As an example Fig. 13 shows the time diagram for a high ohmic fault. The voltage $u_0$ is going towards 55%. At the trigger point the currents can no longer be used for a selective fault location.

Fig 13: High ohmic fault

In contrast to the conventional approach the selective fault location was successful by using the qu-algorithm.

CONCLUSION

In this contribution we have discussed the basics of an earth-fault and the effects of the impedance at the fault location on the behavior of the transients in the zero-sequence system. To see the limits of conventional transient relays, we have elaborated different situations, which may occur in every real-world network. According to these requirements we have presented a new algorithm. Field tests and first practical experiences show the effectiveness of this new concept for transient relays.

REFERENCES


