QU2 - ALGORITHM FOR DETECTING EARTH-FAULTS

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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 first main advantage of this treatment of the neutral point is the fact, that in most cases the system is self-healing, as the arc distinguishes without any intervention of the protection system[1]. The second main advantage is the possibility of continuing the network operation during a sustained earth fault. As a consequence, the number of interruptions of the power supply for the customer is reduced. But with this improved power quality problems arise for the selective detection of earth faults. The conventional relays are designed only for non-intermittend low ohmic earth faults and for non meshed grids.

With the new adaptive algorithm directional earth fault detection from low ohmic up to some kOhm is possible in non-meshed and meshed networks.

Up to now the preferred fields of application for transient relays in the medium voltage were large unmeshed cable networks. With the new adaptive algorithm the relay is also applicable for rural networks, where the probability of a high ohmic earth fault is much higher.

This new adaptive algorithm is now also able to suppress crosstalk from the load current to the zero-sequence-system. Therefore transient relays with this new adaptive algorithm can be used successfully in meshed networks with non negligible crosstalk.

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

BASICS OF THE EARTHFAULT

To explain the behavior of a single line earth fault, two different processes can be superposed [3], [6], [9]. The following two processes are starting at the same time, but with different duration:

- discharge of the faulty line over the earth
- charging of the two healthy lines over the earth

The two processes are ending in the stationary state of the earth fault. The explanation of the two 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 *Fig. 1*.

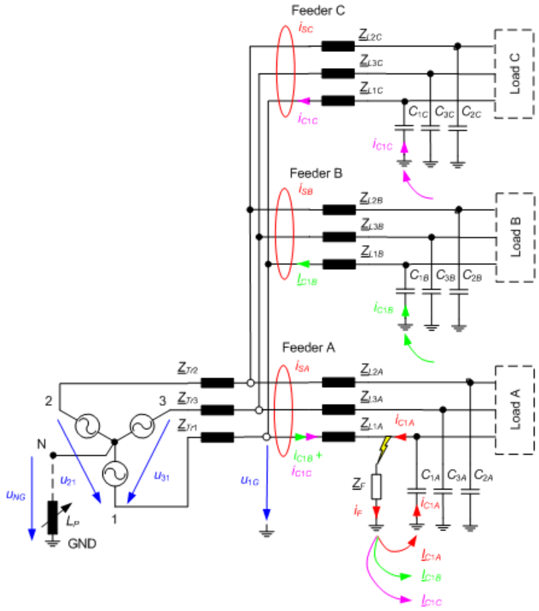

Fig. 1: Discharge of the faulty line over the earth

Discharge of the faulty line over the earth

The lines can be considered as a distributed lattice network, consisting of a complex serial impedance $\underline{Z}_{LXX}$ and a line-to-ground capacitance $\underline{C}_{XX}$ .The greatest probability for the first ignition is near the maximum of the line-to-ground voltage u_{1G}. 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 in both directions to the ends of line 1. A reflection of the waves occurs at the end of the line respectively at every change of the image impedance of the line. 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 $\underline{Z}_L$ of line 1 in the faulty feeder and in the healthy feeders
- Impedance $\underline{Z}_F$ 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 it 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 line-to-ground voltages is destroyed.

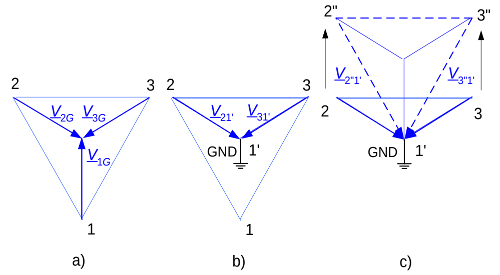

Fig. 2: Change of the voltages during charging process

As the supply-transformer is still delivering a symmetrical three phase system, the two healthy lines will be charged to the line-to-line voltage. This charging process for the network with three feeders is shown in detail in *Fig. 3* .

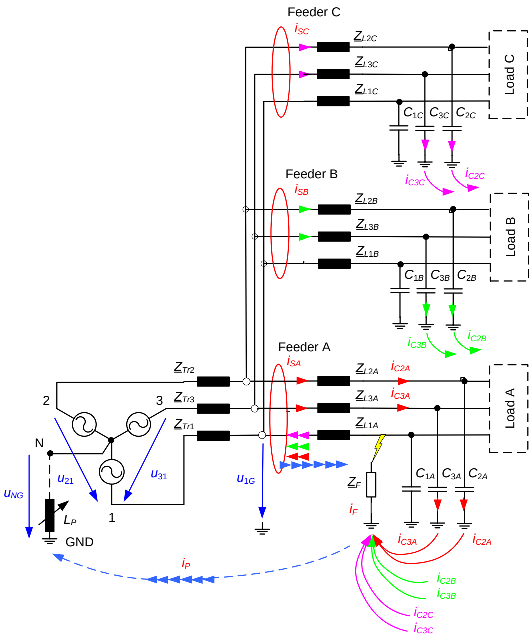

Fig. 3: Charge of the healthy lines over the earth

Important parameters for the behavior of the charging are:

- Capacity of line 2 and line 3 to ground
- Charge of the line-to-ground capacities before the start of the first ignition
- Charge voltage $\underline{V}_{21}$ and $\underline{V}_{31}$
- Leakage inductance of the supply transformer
- Serial line impedance $\underline{Z}_L$ of the lines
- Impedance $\underline{Z}_F$ 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 oscillation. 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 oscillation 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.

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 current. 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 summation of this 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 ignition.

The conclusion is, that the relay in the faulty feeder can only measure the sum of the charging currents of the healthy network in it´s back and that this current has an inverse direction.

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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 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 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 complete compensated. From fig. 3 it is recognizable, 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 more an indication for 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 thwo processes start at the same time.

In the following 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 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 reaches about 40% in the steady state.

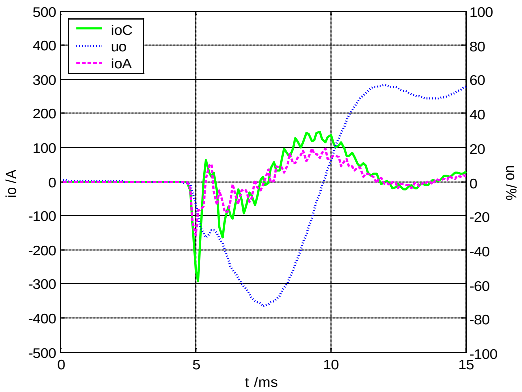

Fig. 4: Two healthy feeders at a low ohmic earth fault

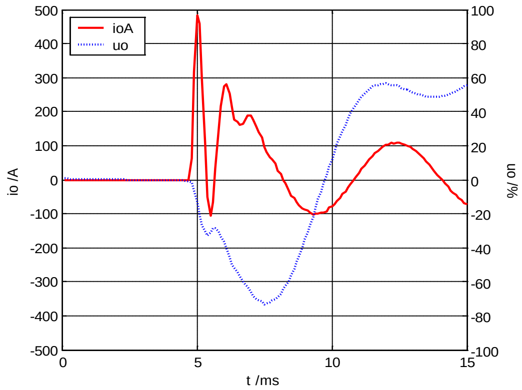

Fig. 5: Faulty feeder at a low ohmic earth fault

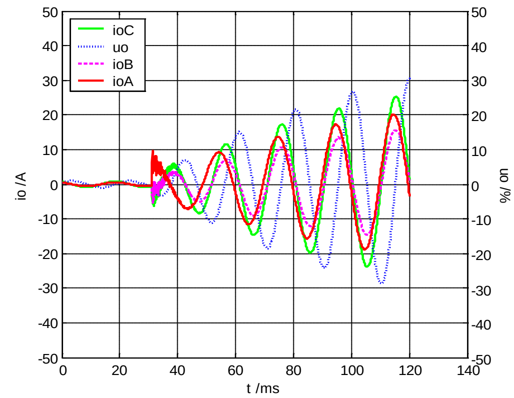

Fig. 6: High ohmic earth fault

QU-ALGORITHM

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 or C, as shown in *Fig. 7*, of our sample-network the charging can be described with equation (1).

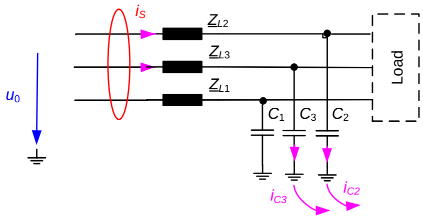

Fig. 7: Charge of one healthy feeder

$$u_0(t) = u_0(t_0) + \frac{1}{C_{eq}} \int_{t_0}^{t} i_S(\tau)\ d\tau \qquad (1)$$

$$u_0(t) = u_0(t_0) + \frac{q_S(t)}{C_{eq}} \qquad (2)$$

Starting the integration at a point where $u_0(t_0) = 0$ results in:

$$u_0(t) = \frac{q_S(t)}{C_{eq}} \qquad (3)$$

Drawing a diagram of this relation, with q_0 on the ordinate and the zero-sequence voltage u_0 on the abscissa results in a straight line with the gradient C_{eq}, which is the equivalent zero-sequence capacitance of the feeder. Subsequently, this diagram shown in *Fig. 8* will be referred to as qu-diagram.

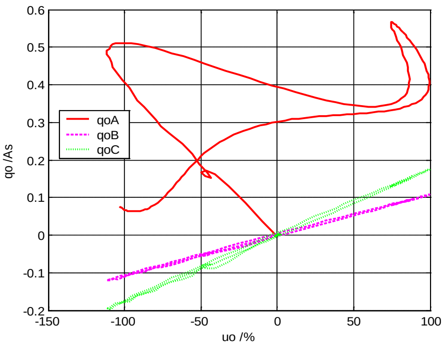

Fig. 8: qu-diagram of the three feeders in case of a low ohmic fault in feeder A

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 from the faulty feeder, it starts with a negative gradient and in compensated networks it is not a straight line. The last statement can be used as additional information for the earthfault detection.

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. 6*

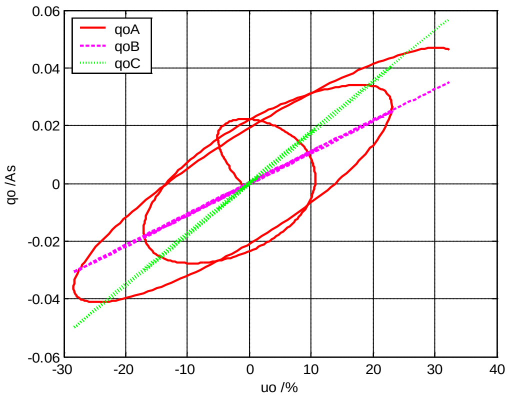

Fig. 9: qu-diagram of a high ohmic fault

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 square algorithm and pattern recognition algorithm are implemented in the relay, in order to improve computational efficiency.

qu-Algorithm 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 doesn't always fall below the preset trigger level
- The zero-sequence current doesn't have a steady state

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

The second item is a problem especially 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 influence the calculation of the fundamental components. The result of this is, with high probability, a complete erroneous decision of the fault direction. This problem doesn't only occur in the faulty feeder, but even in the healthy ones.

Fig. 10 shows, that u_0 doesn't 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.

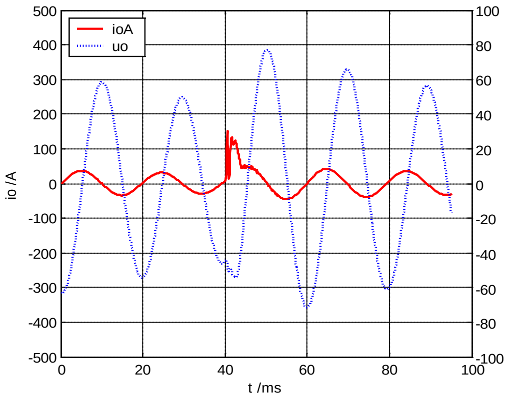

Fig. 10: Faulty feeder at a restriking earth fault

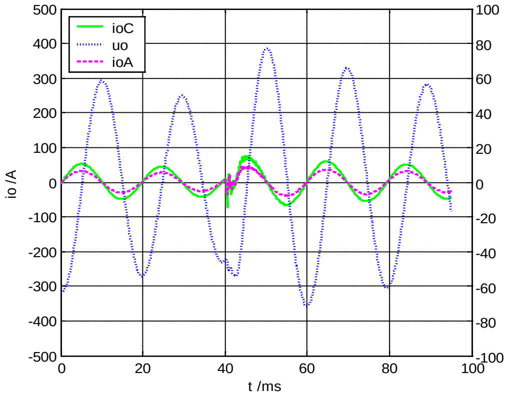

Fig. 11: Healthy feeders at a restriking earth fault

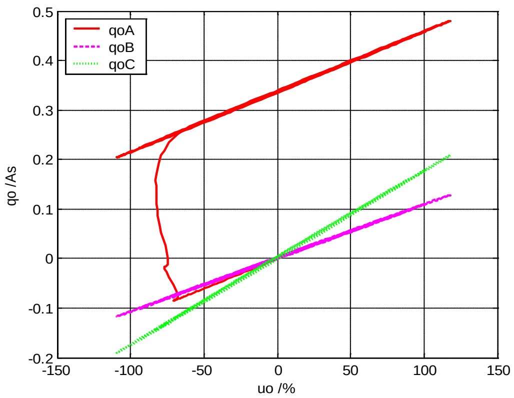

Fig. 12: qu-diagram of a restriking fault

Fig. 12 shows the associated qu-diagram for the restriking fault.

The advantages of the qu-algorithm are:

- Simple evaluation
- No high speed sample rate is necessary. A sample rate of about 2 kHz is sufficient
- Influence of the discharge is reduced due to the integration of i_0
- The integration and evaluation can be done over a half period
- The integration of i_0 over a larger range before the trigger-point enables the detection also of high ohmic earth faults up to some kOhm
- on-line versions of the least squares algorithm [8] and pattern recognition algorithms (e.g. [4]) improve the computational efficiency

The disadvantages of the standard qu-algorithm are:

- Sensitive to analog-digital-converter saturations, as the straight line is modified to a curve
- Sensitive to not negligible phase-splitting
- Sensitive to crosstalk from parallel systems

The first disadvantage is only relevant in case of integration over the complete half period of u_0 and in combination with testing of the feature "straight line" of healthy lines.

The sensitivity against phase-splitting is a general problem of all relays, especially for cos(phi) relays. Using *Fig. 13* the reason of phase splitting in a healthy meshed network will be explained.

Phase-splitting

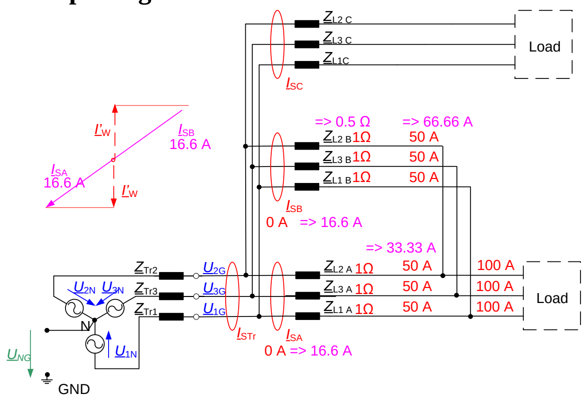

Fig. 13: Phase-splitting in the healthy network

In a symmetrical situation the load current in each phase will be splitted symmetrical to the feeders A and B. In this situation the measured sum-current ($\underline{I}_S$ = 3 $\underline{I}_0$) at the substation will be zero. Due to unbalances in the serial impedances of the lines the distribution of the load current will change. In the example the current in phase 2 is changing from 50 A to 33.3 A respectively to 66.6 A.

Now the sum-currents of the feeders in the substation are no longer zero. In our example the sum-current increases up to 16.6 A and the directions in the two feeders are opposite.

We can find this behavior in any loop, in parallel lines and in meshed networks.

The size of the phase-splitting current depends on:

- load current
- point of load on the loop
- physical arrangement of the asymmetry of the serial impedances [2]
- number of meshes

The asymmetry of a line may be caused for example by the kind of laying the cables, as shown in *Fig. 14* a (for further details the reader is referred to [5],[10],[11]). If the cables are laid in a triangle (see *Fig. 14* b) the mutual coupling of the three phases and therefore the serial impedance is obviously the same.

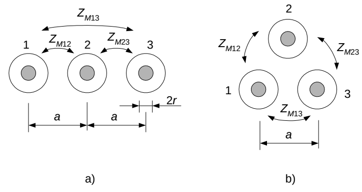

Fig. 14: a) Single conductor cables in parallel
b) Single conductor cables in triangle

A similar situation can be found for overhead lines where an improvement can be made, by transposing the phases.

One possible way to compensate this influence in loops is to measure the currents in all feeders and to add the currents of the feeders, which are switched to a loop. But this version needs a very high number of current measurements and, in addition, always the actual information, which feeders are switched to a loop. The requirements to such a SCADA System would be enormous.

Crosstalk from parallel systems

Systems switched to a loop are also very sensitive to the magnetic coupling of galvanic isolated parallel systems.

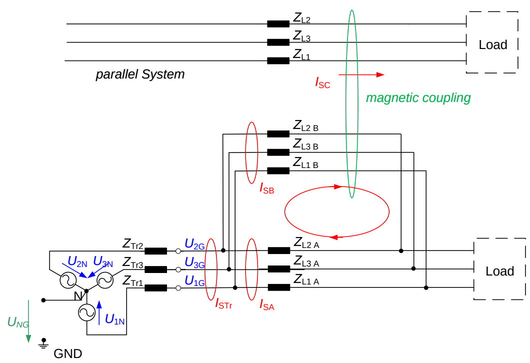

Fig. 15: Magnetic coupling of parallel systems

The influence of the parallel system may be negligible under normal operation, due to the small distances between the three phases. But in case of an earth fault in the parallel system, the currents through the three wires are no more symmetrical, also in healthy feeders (see *Fig. 3*). The asymmetric loading currents can be in the range of 100 A. Therefore the magnetic coupling must be taken into account.

A worse situation arises in case of a cross-country-fault in the parallel system.

Also a phase-splitting in the parallel system can be the reason for a crosstalk.

QU2-ALGORITHM

With the assumption of no change of the crosstalk from a neighbor system and no change of load in the own system during the few periods of interest, a linearization around the working point combined with a nonlinear filtering solves the major problem.

For the explanation real measurements of an earthfault in the 16.7 Hz 110 kV network of the railway will be used. The network has about 1200 A capacitive current and is compensated with several distributed Petersen-Coils.

In the following figures the first channel shows the zero-sequence voltage in the substation.
The next two channels are the sum-currents of two parallel lines with a high current due to phase splitting. These two currents are more or less opposite. These currents include also the smaller zero-sequence currents due to the natural asymmetry of the network.

The last two channels show two independent feeders.

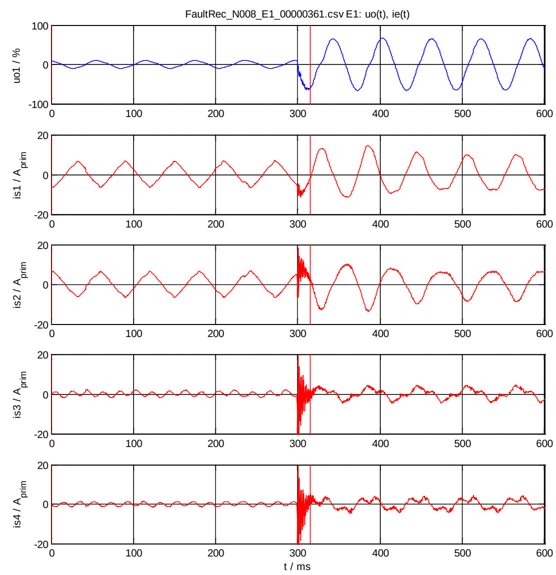

Fig. 16: Zero-sequence-voltage and -currents of four feeders with phase-splitting in feeder 1 and 2

Fig. 16 shows, that the change of currents in the feeders 1 and 2 due to the earthfault is very small.

In *Fig. 17* the corresponding standard qu-diagrams are shown. Comparing to *Fig. 8* or [3], a clear decision, which feeder is the faulty feeder and which are the healthy feeders is not easy, respectively impossible.

As long as the natural asymmetry of the net, represented by u_0, is very small, a linearization around the working point

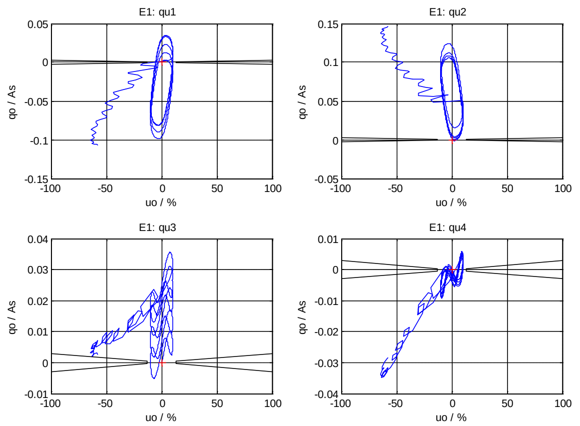

Fig. 17: Standard qu-diagram for the four feeders without correct identification of the faulty feeder

results in relative small inaccuracy of the equivalent model. *Fig. 18* shows the result of the linearization. The first periods are zero and the following periods up to the earthfault have only small variations due to variations in the load.

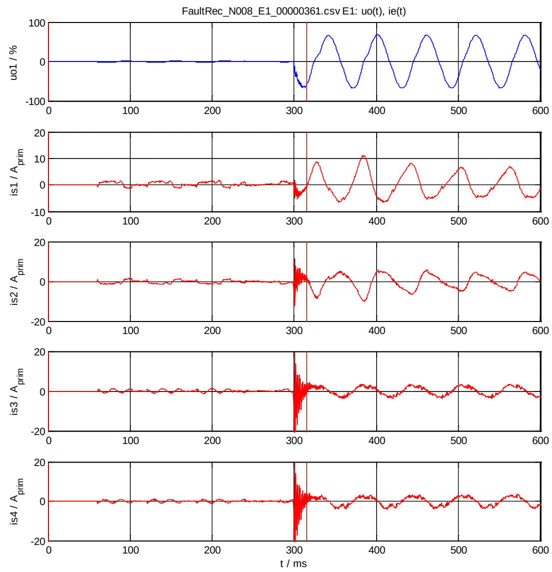

Fig. 18: Currents after linearization at working-point with strong reduction of the phase-splitting in feeder 1 and feeder 2

With an adaptive nonlinear filtering from the first period up to the earthfault, also these values can be reduced.

The parameter of the adaptive filter has an effect on the maximal detectable high ohmic earthfault.

On the other side, the saturation of analog-digital-converter and currents of cross-country faults are also modifying the filter-parameters.

The results of the adaptive nonlinear filtering of the low-ohmic earthfault are shown in *Fig. 19*

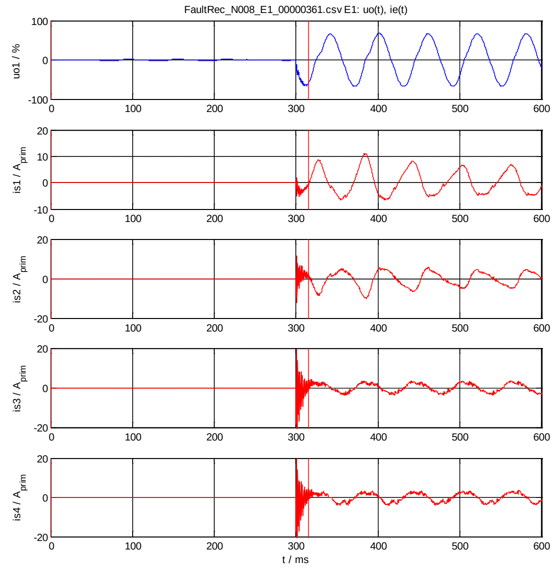

Fig. 19: Zero-sequence- voltage and -currents after adaptive nonlinear filtering. Influence of crosstalk, phase-splitting is reduced and prefault values are set to zero.

In *Fig. 20* the results of this qu-algorithm with additional nonlinear adaptive filtering are shown. Now it is no more a problem to identify the feeder 2 as the faulty feeder.

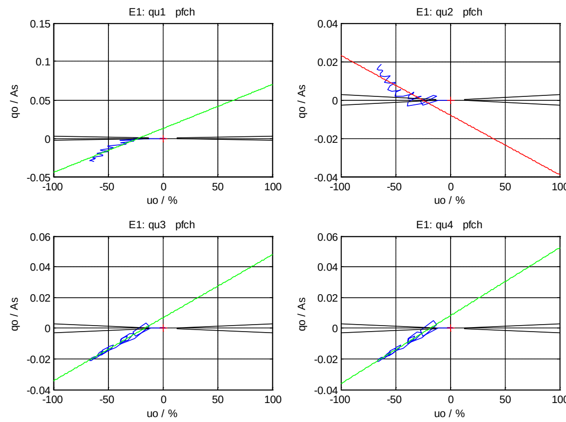

Fig. 20: qu2-diagram with correct identification of the faulty feeder 2

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