NOVEL METHOD FOR SELECTIVE DETECTION OF EARTH FAULTS IN HIGH IMPEDANCE GROUNDED DISTRIBUTION NETWORKS

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INTRODUCTION

An elementary and reliable detection of earth faults in impedance grounded networks results in considerable benefits for the utility both in terms of outage duration and personal safety. This report describes an entirely new, only current measuring method; a method, which fulfils the standards of cost efficiency and reliability. Despite the seeming simplicity of the approach it is also demonstrated that it is an excellent method to detect arcing cable earth faults.

INDICATION OF EARTH FAULTS

There is a need to improve the methods for detection of earth faults in impedance grounded medium voltage cable networks, and make it more reliable, without increasing the investment cost.

A prompt and secure determination of the fault location at a cable fault will have the following advantages:

- *Security* – a faulty cable can be immediately removed without preceding measurement.
- *Speed* – the electric power to affected customers can be re-established without delay by the reconnection of healthy cables.
- *Selectivity* – unselective trip of transformers due to remaining neutral-point voltage can be avoided by improved feeder protection.

MEDIUM VOLTAGE NETWORKS IN SWEDISH URBAN DISTRIBUTION

Secondary substations in Swedish urban distribution are fed by cable networks for medium voltage, normally 12 or 24 kV. The cable networks are impedance grounded in that the transformers of feeding substations are connected to ground by a resistor and often also a reactor.

The medium voltage network is generally operated as a ring network with one normally open point in one of the secondary substations. In the case of a fault within the network, the relay protection in the feeding substation trips the faulty cable and all secondary substations in the affected part will lose the power. The time it takes to restore the operation by reconnection is dependent on how quickly the fault can be localised.

So far, there exists no cost efficient and reliable method to detect single-phase, pass through, earth faults in secondary substations. Conventional technique, based on known technology, involves current and voltage measurement at every substation. Voltage transformers are usually not included in the switchgears of secondary substations and to install them would entail considerable cost.

Earth fault detection based only on current measurement has the prospects to supply all secondary substations in a cable network with equipment for quick and reliable restoration of electric power after a fault. In addition to detection of faults it is also desirable to integrate RTU functionality and communication into one entity to be able to present information in a SCADA system.

BACKGROUND AND THEORY

Traditionally earth faults in reactance grounded networks are detected by measuring the residual current and the neutral point voltage. From this one can either obtain the vectorial product $\mathbf{U}_0\mathbf{I}_0$ or calculate I_0 in combination with $\varphi = \angle\mathbf{I}_0/\mathbf{U}_0$. Regardless of method, one wants to estimate the resistive current component of the residual current through the neutral point resistance and the fault, which principally only exists between these two points. This measuring technique has been employed for a long time and works satisfactorily when the network is reasonably tuned. It is not unusual that the reactance of the reactor with time, after changes in the network, deviates from the total capacitive reactance of the network. Such discrepancies cause a deterioration of the sensitivity to high-resistive earth faults.

This report describes a new method to detect earth faults. Instead of the zero sequence components ($\mathbf{U}_0$ and $\mathbf{I}_0$), one studies the phase currents, for they change in specific ways at single-phase earth faults. To generalize, one can say that the phase current changes between the fault position and the neutral point are different, while they are the same or very similar in healthy parts of the network. Since even legitimate load changes cause phase current change, it will be demonstrated how these appear in comparison to changes caused by a single-phase earth fault. Load changes in a distribution network with Δ/Y-connected loads cause either positive sequence current increase or equally large, but opposite, positive and negative sequence increase.

The understanding of this new method is facilitated by a 3-

phase approach, as opposed to using the traditional symmetrical components. What separates a faulty feeder from a healthy one? This question is answered if we study the following simplified network.

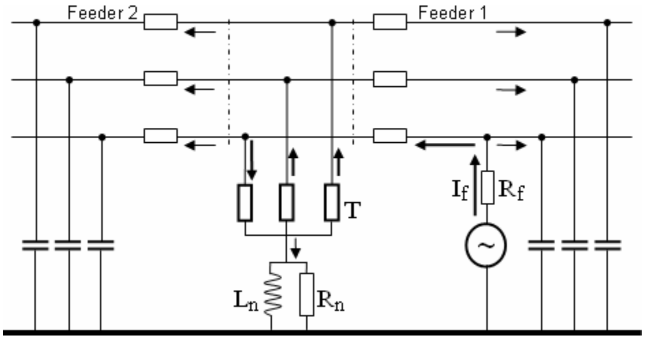

Fig. 1 Simplified network with 2 feeders and a single-phase earth fault in Feeder 1, illustrating the Thévenin current changes.

Figure 1 illustrates that the fault current from the fault position will be distributed so that the current in the faulty phase-conductor constitutes the entire fault current, while the current in all healthy phase conductors is determined on their capacitance to earth. The model in Figure 1 is much simplified, but still describes the phenomenon for the new measuring method. A better model includes other qualities of a network, such as, for instance, loads varying with time.

In order to design a detector utilising the above described phenomenon, one needs to be able to measure current changes with precision. One way to measure current changes is to compare the current of one cycle with that of the previous cycle. Not only earth faults but also loads will effect current changes. Can these be distinguished from one another? Below follows a demonstration of two cases with simultaneous load current change and high-resistive earth fault.

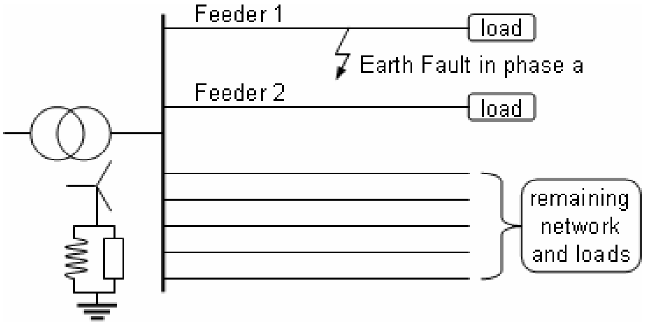

Fig. 2 Network model simulated in EMTDC[1]. The network is assumed to have U=10.7 kV, X_n=122 mH (162 A), Capacitance/phase = 27.9 µF, R_n = 1.2 kΩ (5 A) and loads = 3.8 MVA. C_{F1} = 0.68 µF (4 A), C_{F2} = 2.26 µF (13 A), x_r=0.08 and S_n=50 MVA.

Let us first study two earth fault cases without a load change. Figure 3 below illustrates clearly that the current change in the faulty phase of Feeder 1 is considerable compared with the faultless phases, while current changes are comparable in all phases of Feeder 2. Normally, there is a minor difference between the faulty and the faultless phases in healthy feeders, because the current in the latter must pass the transformer.

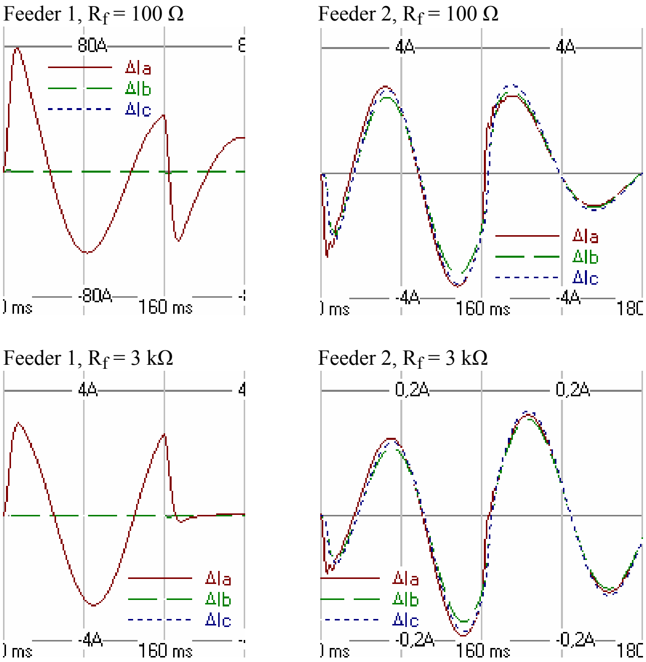

Fig. 3 Simulated faults from the network model in Fig. 2. Notice that C_{F2} is set to 2.26, 2.16 and 2.36 µF for phases a, b and c so as to be able to distinguish the individual phases in Feeder 2. The faulty phase voltage is 80° at fault time.

Figure 4 displays how a simultaneous load change can affect the measurement; of a 2-phase load increase of 2 kW between phases b and c, and of a 3-phase load increase of 10 kW.

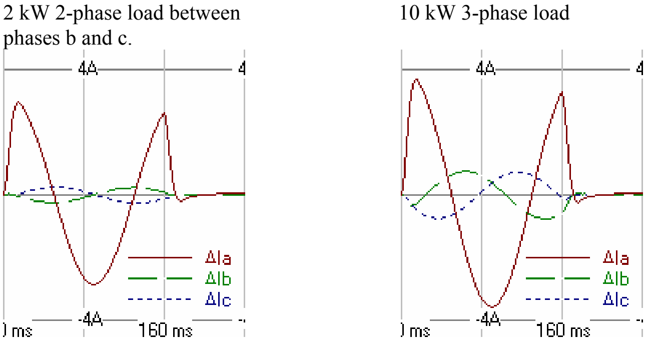

Fig. 4 Single-phase earth fault with R_f = 3 kΩ and simultaneous 2-phase and 3-phase load increase in Feeder 1.

The figures above illustrate that the current change in the faulty phase is significant also at high-resistive earth faults. The curves from Feeder 2 at a simultaneous load change are identical to the corresponding curves in Figure 3.

The measuring method is based on the asymmetry between current changes in the three phases, illustrated in the figures above. The asymmetry is considerable at low-resistive earth faults but decreases with growing fault resistance. The level of sensitivity is therefore limited by possible “continuous” load current changes and on the accuracy of measurement. It should also be pointed out that the method includes both transient and steady state measurement. The method is not

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[1] Simulation software, Manitoba HVDC Research Centre, Canada.

directional but rather fault pass-through sensitive, which means it adjusts to the existing network configuration. Since the method is based on current asymmetry within a specific time window it is not sensitive to CT angular errors or to the tuning of the neutral point reactor.

FIELD TEST

Tests have been made at Göteborg Energi. The voltage was 10.5 kV and the reactor was set to X_n="158 A" and R_n = "45 A". The healthy feeder has a total capacitive current to earth of 13.1 + 5.5 A and the faulty feeder has the capacitive current of 3.07 + 1.77 + 11.2 A.

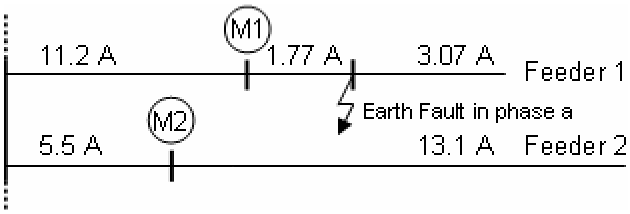


Fig. 5 Test network at Göteborg Energi, where M1 and M2 are the measuring points.

Detectors were placed in several secondary substations. Here, only measurements from secondary substations at M1 and M2 are demonstrated. The measured curves are from the built-in Transient Fault Recorder of the Detector.

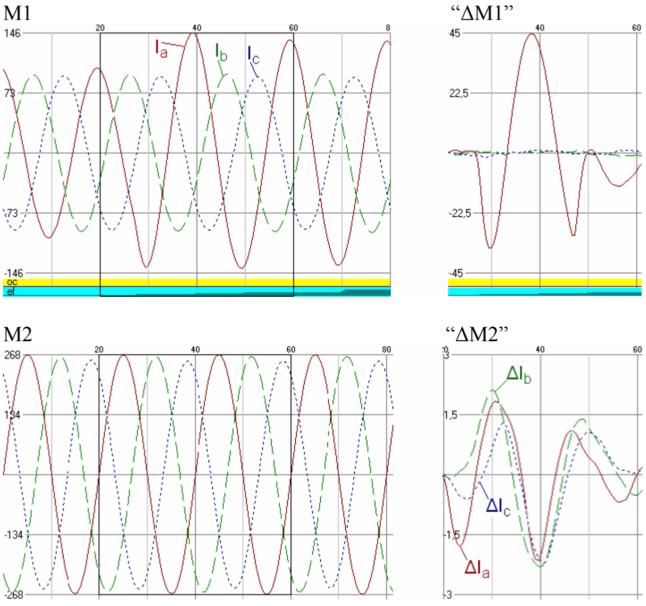


Fig. 6 Detector fault recordings from M1 and M2 in Fig. 5, when R_f = 133 Ω. The left curves show the current and the right show the current change.

The curves to the right in Figure 6 show the above mentioned phenomenon with the total fault current in the faulty phase at M1 and the changes of the 3 phase currents approximately the same at M2. From the curves, one can estimate that the max. change at M2 for $I_a+I_b+I_c \approx 8$ A over 2 cycles, i.e. 5.7 A_{RMS}. The theoretically calculated residual current of 6.5 A_{RMS} at a fully tuned network corresponds well to the reference measurement 5.8 A_{RMS}. Total load through M2 was 3.4 MVA.

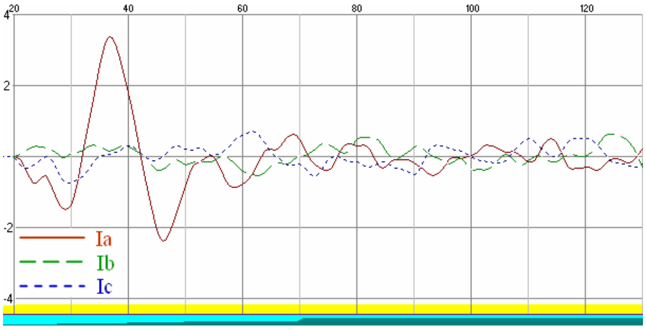
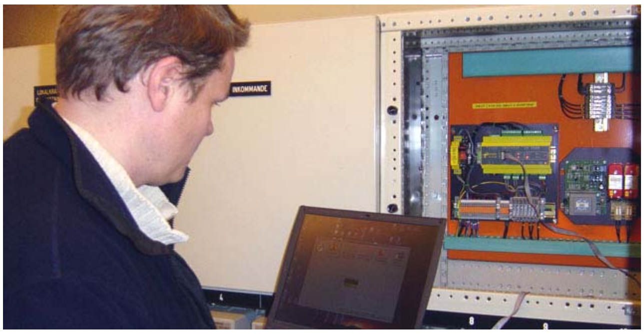


Fig. 7 Detector fault recording showing the current changes "ΔM1" at M1 when R_f = 2460 Ω. Note the horizontal lower bar at 40 ms, showing that the asymmetry is recognised.

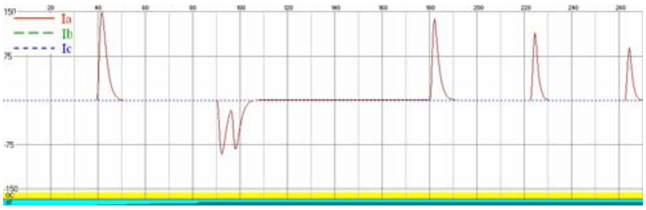
Figure 7 illustrates the top value I_a = 3.4 A, i.e. 2.4 A_{RMS}. A theoretical estimation of the residual current gives 10500/2593 = 2.3 A_{RMS} when a fully tuned network. It should be noted that measurement errors and load changes are more significant at high-resistive faults. Still, the current change in the faulty phase is apparent. The load through M1 was at the time of the fault approximately 1.4 MVA.



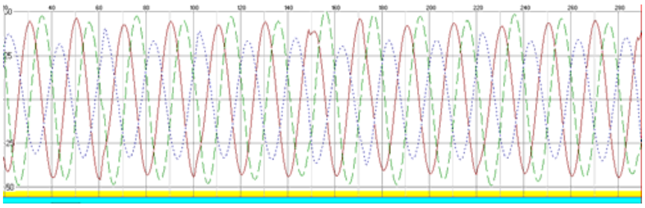
Picture 1 ProTrol IPC4010 integrated controller installation at M1.

ARCING EARTH FAULTS

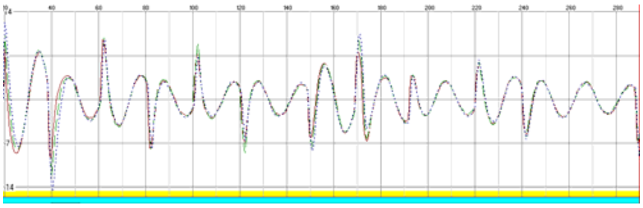
The difficult task of providing the detection of arcing earth faults may be solved by realising that the 3 phase currents contain more information than only the residual current. Around 50 tests have been completed with unequivocally good results. Below is an example of a fault from tests carried out at a Fortum primary substation.



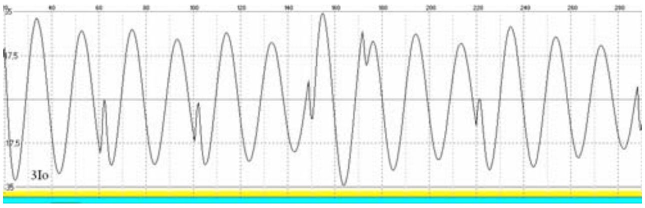
(a) Phase currents in the faulty feeder with no load (Feeder 1)



(b) Phase currents in the healthy feeder (Feeder 2)



(c) Phase current changes (ΔI) in the healthy feeder (Feeder 2)



(d) The residual current in the healthy feeder (Feeder 2)

Fig. 8 Arcing earth fault registered at the Fortum primary substation. Network data: X_n="100A", X_C="90 A", R_n="4 A". The faulty cable was a short unloaded 12 kV isolation damaged cable placed on the ground in the switchyard. The network is a mixture of overhead and cable feeders.

Note also that the current changes in the healthy feeder are basically the same while the current peaks from the arcing flash-over in Feeder 1 are very high and asymmetrical. The currents in the figures are low-pass filtered so that the actual current levels of the current peaks are 0.5-1 kA, since they are generally only restricted by the grounding network resistance.

Figure 8 demonstrates that the residual current is significant also in healthy feeders. The shape of the curves can easily be misinterpreted by steady state measuring protection.

SYMMETRICAL COMPONENTS

When analysing earth faults, symmetrical components are normally used. The observations regarding current changes at single-phase earth faults are confirmed in Figure 9 below.

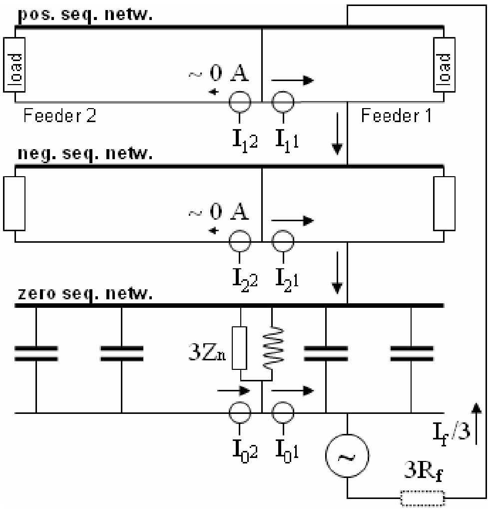


Fig. 9 Equivalent network for single-phase earth fault described with symmetrical components.

In Figure 9 is shown that the current changes in the healthy Feeder 2 essentially occur only in the zero sequence network, i.e. $I_12 \approx 0$ and $I_22 \approx 0$. The equations (1-3) below reveal the same results as the 3-phase reasoning earlier.

$$I_A = I_0 + I_1 + I_2$$
$$I_B = I_0 + a^2I_1 + aI_2$$
$$I_C = I_0 + aI_1 + a^2I_2$$
$$\text{Where } a=\angle 120° \text{ and } a^2=\angle 240° \qquad (1)$$

With the approximation that $I_01 \approx I_11 \approx I_21 \approx I_f /3$, the equations for Feeder 1 give the following results:

$$I_{A1} = I_{01} + I_{11} + I_{21} \approx I_f$$
$$I_{B1} = I_{01} + a^2I_{11} + aI_{21} \approx 0$$
$$I_{C1} = I_{01} + aI_{11} + a^2I_{21} \approx 0 \qquad (2)$$

And for Feeder 2:

$$I_{A2} \approx I_{02}$$
$$I_{B2} \approx I_{02}$$
$$I_{C2} \approx I_{02} \qquad (3)$$

Equation (2) demonstrates that the phase current change in essence corresponds to the entire fault current, and equation (3) illustrates that all phase current changes are approximately the same and that they are determined by the feeder capacitance to earth.

SUMMARY

This new method for selective detection of earth faults generates new possibilities. Every secondary substation can be supplied with equipment that accurately measures and indicates what secondary substations a fault has passed (Fault Pass Through). While the Detector is based on current measurement only, it is unproblematic to complement standard RMU switchgears without installing voltage transformers.

The new method will also improve the dependability and reliability of the relay protection for earth faults in feeding primary substations. The existing earth fault protection for arcing earth faults in cable networks are not sufficiently reliable. A consequence of this is that a faulty cable does not trip in time. The protection for high neutral voltage thereby disconnects the transformer. Consequently, an additional number of customers are disconnected and affected.

Swedish electricity distribution today encounters a growing demand on increased availability at the same time as authorities and customers require low fees. This means that utilities have limited funds for investments in the distribution network and, therefore, must look for smart solutions to fulfil the new requirements.