Detection of earth fault in a medium voltage distribution network

T. Henriksen, A. Petterteig

Abstract—The application of sophisticated computational models are frequently limited by the available input data. This paper presents results from measurements where a single phase to ground fault was introduced in a distribution network grounded by an arc suppression coil. The non-symmetrical conditions prior to the fault limit the possibility of the detecting a high impedance fault when using phasor variables. These non-symmetrical conditions depend on parameters that are normally not known with sufficient accuracy but the performed measurements give the relevant information for the actual network. The time domain measured signals have been converted into time variable phasors and it is shown how the phasors are influenced by the transients due to the fault initiation and the disconnection of the faulty feeder. Most of the tests where made by introducing a permanent fault, but a series spark gap was introduced in some measurements. The gap caused multiple extinctions and re-ignitions of the fault current that became substantially distorted.

The fault initiation causes current spikes that can be used to detect the fault and identify the faulty feeder. The spikes are reduced by the fault resistance and the measurements indicates 1 kΩ as an upper limit for detecting the fault, while the phasor analysis indicates 5 kΩ as an upper limit.

Keywords: Arc suppression coil, ground fault, measurements, fault detection, non-symmetrical conditions

I. Introduction

A frequent limitation in the accuracy of computed transients is the knowledge about the required input data. The positive sequence parameters at power frequency are normally known with sufficient accuracy, but the knowledge about non-symmetrical network conditions including return current in the ground is often limited in particular for higher frequencies. It is therefore important to perform measurements in actual networks in order to get reliable results. This paper focuses on non-symmetrical condition in normal operation and the losses involved in a single phase to ground fault in a 22 kV network grounded by an arc suppression coil. The paper is mainly based on measurements in a distribution network.

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II. Test set-up

The measurements took place in a 22 kV radial network that was fed from a 66 kV network via a Yyn transformer. There were three feeders (A, B and F) connected to the bus bar in the substation during the measurements. One feeder (F) was interrupted after 500 m and a ground fault was introduced at the end of that feeder. The feeder is in normal operation longer and the remaining part of the feeder was connected to another substation during the measurements. The length of the two healthy feeders is 48 km (feeder A) and 73 km (feeder B) and a major part of these feeders is overhead lines. The contribution from each healthy feeder to a low impedance single phase to ground fault current is respectively about 9.3 A and 12.4 A. The voltage drop of the faulty feeder, i.e. the drop between the bus bar and the fault location was insignificant during the performed measurements and is ignored when analyzing the results.

An adjustable arc suppression coil with a 1.7 kΩ parallel resistance is connected to the neutral of the substation transformer in the same way as described in [1] and shown in Fig.1. The resistance is much higher than the one in [1].

The following parameters were varied during the test: The degree of compensation, the status (connected/disconnected) of the parallel resistance and the value of a fault resistance that was connected in series with the fault connection from the phase conductor to ground.

The single phase to ground faults did not cause any detectable influence on the line-to-line voltages, which were practically equal to 22 kV during the tests. The results presented in this paper are therefore limited to zero sequence components. Fig. 1 shows a simplified circuit diagram that includes the components that were varied during the measurements and the most important measured variables.

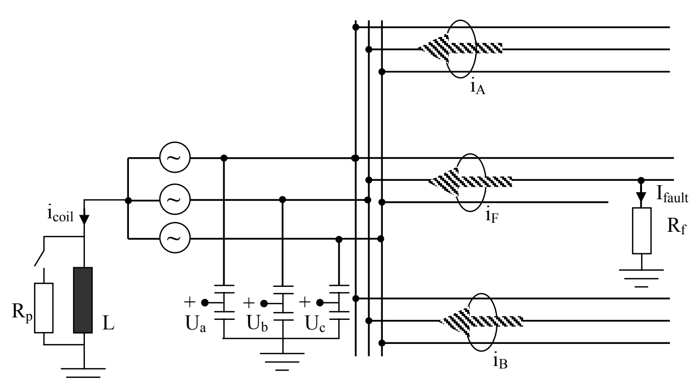


Fig. 1 Simplified circuit diagram.

The bus bar voltages (phase to ground) were measured by specially designed capacitive voltage dividers and the sum of the currents of each feeder was measured by Rogowski coils. The currents measured by the Rogowski coils and the current of the arc suppression coil (incl. the parallel resistance) were also measured by inserting small resistances in the existing conventional current measuring circuits. In total 10 measuring signals were connected to a transient recorder. The sampling interval of the recorder was 50 µs and the recorded interval was 6.5 s with 12.5 % pre-trig.

The ground fault current was measured at the fault location by a clamp-on current probe connected to a storage oscilloscope.

The measurements based on the existing current transformers turned out to be very questionable. The reason was probably a combination of small voltage signals and several connections from the transient recorder to ground.

Some additional measurements were made without any fault to establish the resonance curve. The degree of compensation was then varied and the steady state zero sequence bus bar voltage was recorded. These results give information about non-symmetrical conditions in the network when there is no fault and that information is important when analyzing the measurements obtained with a high fault resistance.

III. Faulty feeder identification

The influence on the line-to-line voltages from a single phase to ground fault is insignificant and the identification of such a fault must be based on the zero sequence voltage and current components. The most commonly applied methods are based on phasor variables and the fault is typically detected based on some threshold for the zero sequence voltage. The faulty feeder is as next step identified based on an equivalent impedance or power flow.

An alternative method is to focus on the transient currents caused by the fault initiation. The results from the measurements were analyzed keeping both methods in mind. The time domain signals were converted to time variable phasors based on the formula:

$$\mathbf{F}(\mathbf{t}) = \frac{\sqrt{2}}{\mathbf{T}} \int_{\mathbf{t}-\mathbf{T}}^{\mathbf{t}} \mathbf{f}(\tau) \cdot \exp(-\mathbf{j}\omega\tau) \cdot \mathbf{d}\tau \qquad (1)$$

where f(t) is the time domain signal and T is one (50 Hz) period. The formula corresponds to (2) in [2] except for the scaling factor √2.

IV. Limitation in fault detection due to non-symmetrical conditions

A single phase to ground fault is in principle detected because it introduces a non-symmetrical condition in the network. The non-symmetrical condition when there is no fault is thus an important parameter when considering the possibility of detecting high impedance faults. The degree of compensation was in a separate set of measurements varied slowly and the maximum magnitude of the zero sequence voltage was recorded. These measurements were made both with and without the parallel resistance connected. The results were respectively 439 V and 4042 V. The line voltage was in both cases 22 kV.

Fig. 2 shows a simplified Norton equivalent for the zero sequence system seen from the bus bar. C_0 is the zero sequence capacitance per phase, L the inductance of the arc suppression coil and G_0 the resulting conductance of the network per phase. The equivalent is based on Fig. 2 in [3]. The value of the parallel resistance (R_p) is known. It is then from the two measured voltages possible to determine the magnitude of the current source K in Fig. 2. The value became 0.26 A. Connecting the neutral of the transformer to ground gives a current equal K when there is no fault.

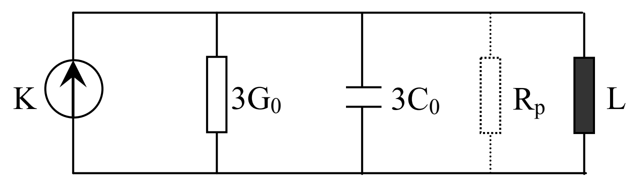


Fig. 2 Norton equivalent for the zero sequence system when there is no fault.

The equivalent circuit in Fig. 2 can also be used when there is a single phase to ground fault, by connecting the fault current in parallel with K. K is caused by non-symmetrical conditions and its phase is unknown. This means that the magnitude of the fault current must be at least twice the magnitude of K in order to be sure that the fault increases the magnitude of the zero sequence voltage (U_0). K represents the sum of the contributions from the non-symmetrical conditions of each feeder. The contribution from one feeder may exceed K. The sum of the three phase currents of a feeder during a single phase to ground fault consists thus of two contributions: one due to the fault and one related to K. The non-symmetrical conditions imply that the fault current must be above some minimum value in order to be detected by phasor variables. We estimate that it should at least be 4 times K, which means 1 A in the actual case. A fault current of 1 A corresponds to a fault resistance of about 10 kΩ. The value of K is normally unknown and may vary e.g. depending on weather conditions. The practical upper limit for the fault resistance for faults to be detected by phasor variables is therefore lower than 10 kΩ.

Some other measurements were made in the same network about one year after the measurements described in this paper. It was during those measurements observed that a single phase to ground fault with a 46 kΩ fault resistance caused a **reduction** in the zero sequence voltage.

V. PHASORS OBTAINED FROM TIME DOMAIN MEASUREMENTS

A single phase to ground fault does practically not influence the line voltages and it is normally sufficient to isolate the fault within seconds. Conventional protection is based on phasor analysis and the phasors obtained from the time domain measured quantities by using (1) will be presented here for two of the test cases where the coil compensated 80 % of the capacitive fault current. Special attention is paid to the initiation and the clearance of the fault.

Case 1 has the following characteristic:

- no fault resistance
- the parallel resistance is connected 1700 ms after the fault initiation
- the faulty feeder is disconnected after 2040 ms

Case 2 has the following characteristic:

- 1 kΩ fault resistance
- no connection of the parallel resistance
- the faulty feeder is disconnected after 1550 ms

Fig. 3 shows the time domain variation of the zero sequence voltage for the two cases during the fault initiation and its disconnection. Fig. 4 shows the variation due to the connection of the parallel resistance in case 1. The zero sequence voltage was in steady state conditions in the recorded time intervals not shown in Figs. 3 and 4.

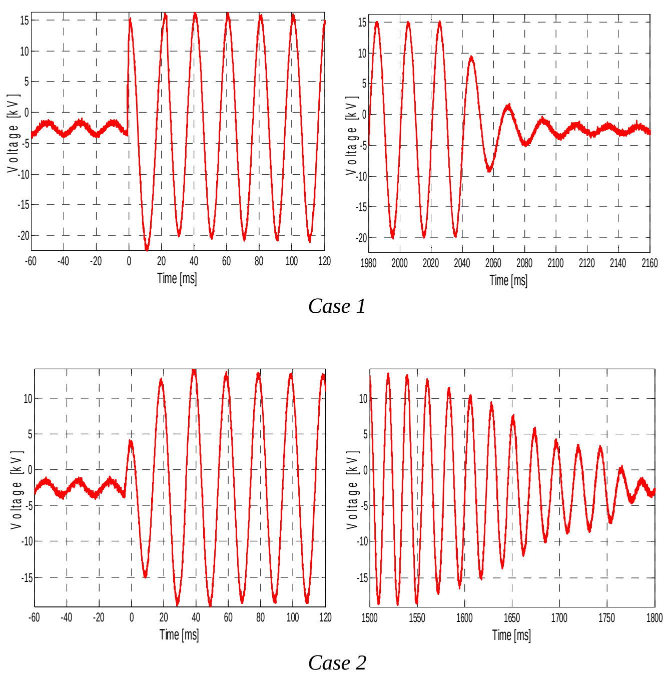


Fig. 3 Measured zero sequence voltage variation (time domain) during fault initiation and fault disconnection.

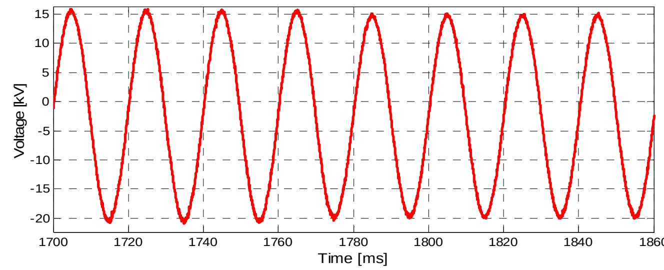


Fig. 4 Voltage variation due to the connection of the parallel resistance in test case 1.

Fig. 5 shows the magnitude of the calculated phasor voltage.

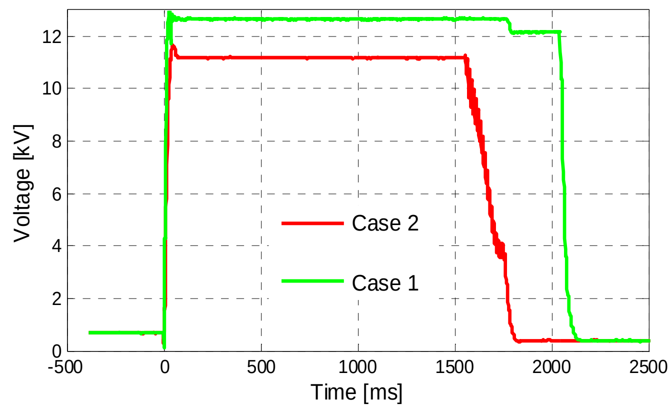


Fig. 5 Magnitude voltage phasors.

Fig. 6 shows the phase of the zero sequence voltage form test case 1. It is seen that there is a linear decrease in the phase. The reason is that the actual power frequency is not exactly 50 Hz. A deviating power frequency causes a linear variation in the phase and it is possible to determine the actual frequency from the linear variation in Fig. 6. The actual frequency was 49.86 Hz.

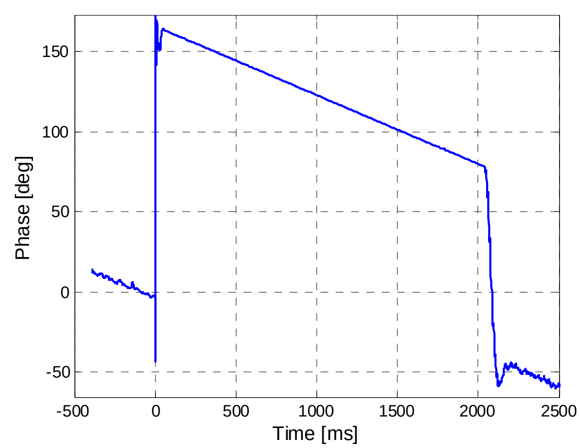
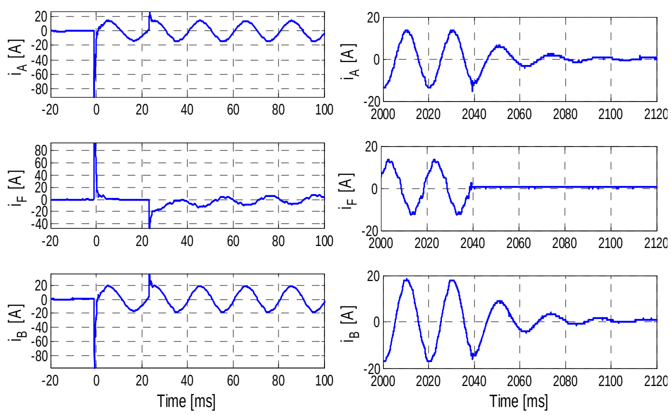


Fig. 6 Phase variation zero sequence voltage, test case 1.

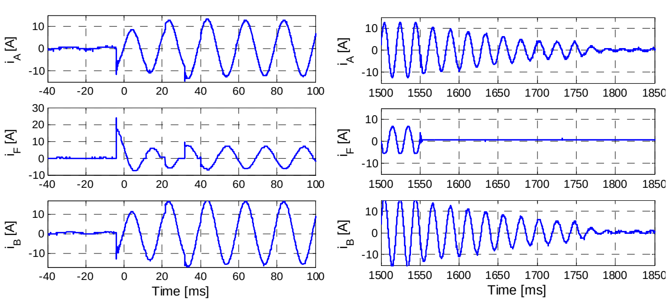
The time domain variation of the three feeder currents for test cases 1 and 2 is shown in Figs. 7 and 8. Fig. 7 focuses on the fault initiation and its disconnection as for the voltage in Fig. 3. Fig. 8 focuses on the variation due to the connection of the parallel resistance.

The phasor variables corresponding to Figs. 7 and 8 are shown in Fig. 9. The phase in Fig. 9 is actually the difference between the phase of the current and the zero sequence voltage of the bus bar.

The time variables in Figs. 7 and 9 are zero when the fault is initiated and the existing ground fault protection disconnects the faulty feeder after specified time. That time was adjusted during the measurements and was in the range 1 s to 2.5 s. The parallel resistance is further connected (if it is not already connected) after some specified time to make it easier to identify the faulty feeder.



Case 1



Case 2

Fig.7 Current variation (time domain) during fault initiation and fault disconnection.

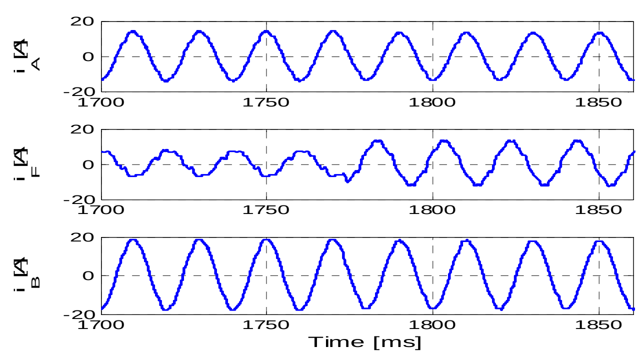
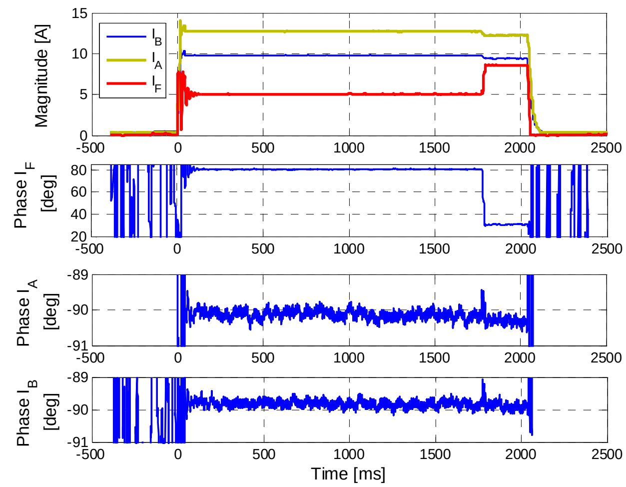
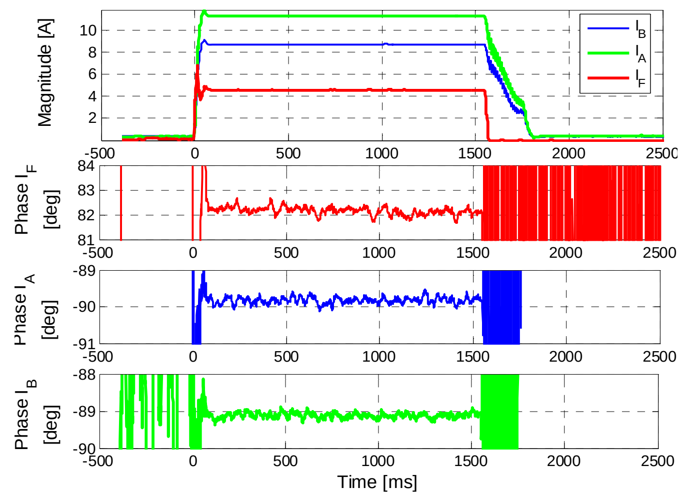


Fig. 8 Current variation due to the connection of the parallel resistance in test case 1.



Case 1



Case 2

Fig. 9 Measured feeder currents presented as phasors.

The connection of the parallel resistance takes place after about 1.7 s in case 1 and Fig. 5 shows that the connection causes a moderate reduction in the magnitude of the voltage. The magnitude of the currents of the healthy feeders is reduced accordingly. The current of the faulty feeder is **increased as shown in Fig. 9**. The contribution from the healthy feeders and the coil is reduced, but there is an additional contribution from the resistance. The phase of the fault current was reduced from about 80 deg. to about 30 deg. when connecting the parallel resistance. The phase of the current of the healthy feeders is hardy influenced by the connection of the resistance.

The parallel resistance was not connected in case 2 and disconnecting the fault gives an oscillating zero sequence current with a moderate damping in the healthy feeders as seen in Fig. 7. Connecting the resistance gives a rather strong damping as shown for case 1. The influence from the damping on the phasors is seen in Fig. 9. There is practically a step in the magnitude when the resistance is connected and a gradual reduction when it is disconnected. There is in both test cases a very strong variation in the phase after the disconnection of the fault.

The most important results in Figs. 5 and 9 are:

- There is a very short transition period to a new steady state condition when the fault is initiated.
- The transition period after the disconnection of the fault can be much longer, but that period is not very important.
- The phase of the current of the healthy feeders is negative and the magnitude should be close to, but less than 90 deg. The magnitude of the phase partly exceeds 90 deg. due to the non-symmetrical conditions of the network in normal state, when there is no fault.
- Connecting the parallel resistance reduces the phase of the current of the faulty feeder very significantly. This makes it much easier to identify the faulty feeder. The fault current is increased from 5 A to 9 A due to the parallel resistance (and the zero sequence voltage is reduced from 12.7 kV to 12.2 kV).

VI. TRANSIENT RESPONSE

The initialization of a single phase to ground fault causes a discharge current that gives current spikes when the fault resistance is low. The polarity of the spikes is the same for the healthy feeders and opposite for the faulty feeder as shown in Fig. 7. The spikes can therefore be utilized both to detect the fault and to identify the faulty feeder. Increasing the fault resistance reduces the spikes. Fig. 10 shows the initial part of the current of the faulty feeder obtained for different values of the fault resistance. (Time displacements are introduced in Fig. 10 to separate the various curves.) The arc suppression coil compensates 80 % of the capacitive fault current, but the coil has an insignificant influence on the spikes.

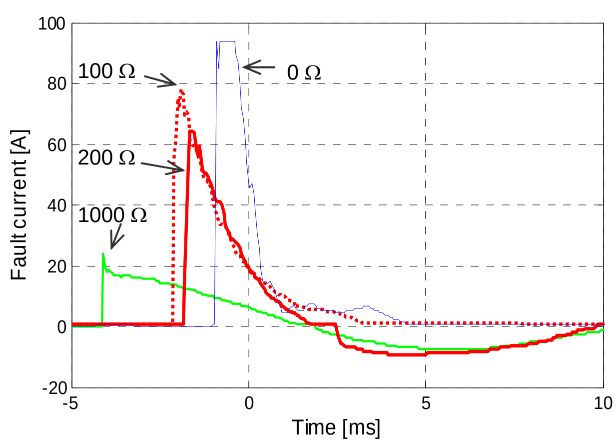


Fig. 10 Initial part of measured fault current.

Table 1 compares the initial peak with the amplitude value of the calculated steady state fault current when the arc suppression coil is disconnected.

The initial peak depends on the value of the zero sequence voltage at the instant of the fault initiation and lower values than the one in Table 1 may occur. It is therefore clear from Fig. 10 and Table 1 that one cannot be sure to detect a single phase to ground fault based on the initial transient when the fault resistance is 1000 Ω or higher.

TABLE 1 COMPARISON INITIAL AND STEADY STATE FAULT CURRENT

Fault resistance[Ω]	Initial peak [A]	Steady state amplitude [A]
0	> 94	30.7
100	78	30.3
200	64	29.0
1000	24	15.5
3000	5.6	5.9

VII. COMPARING STEADY STATE MEASUREMENTS WITH A SIMPLIFIED COMPUTATIONAL MODEL

A very simple model was established based on a Thevenin equivalent seen from the fault location. The voltage source of the Thevenin equivalent was set equal to the (symmetrical) phase voltage and the impedance of the equivalent was determined from Fig. 2 ignoring G_0 and assuming K equal to zero. The fault current was calculated from the Thevenin equivalent and the contributions from each of the healthy feeders, the arc suppression coil and the parallel resistance were determined as a second step. The results from one measurement with 100 % compensation, the parallel resistance connected, and zero fault resistance were used to determine the parallel resistance and the zero sequence capacitance for each of the healthy feeders. The zero sequence bus bar voltage was here set equal to 22 kV/√3. The simplified model is the model that one would use based on the data normally available.

Table 2 summarizes the deviation between the measured feeder currents and the corresponding computed values.

TABLE 2 MAXIMUM DEVIATION BETWEEN MEASURED AND COMPUTED FEEDER CURRENTS

Fault resistance [Ω]	Compen-sation [%]	Parallel resistance connected	Maximum deviation [%]
3000	80	yes	13
1000	80	yes	11
1000	80	no	5
200	80	no	5
100	80	no	5
0	80	no	6
0	100	yes	2
0*	100	yes	3
100*	100	yes	3
100	100	yes	1
100	0	no	3
0	0	no	4

* a 20 mm spark gap was here connected in series with the fault resistance

The deviation is 6 % or less for most of the performed tests. It seems that such a level must be expected when no detailed knowledge is available about the actual network. The 13 % deviation for 3000 Ω fault resistance is probably due to non-symmetrical conditions since the deviation is 6 % for feeder A and 13 % for feeder B. The same argument does not apply when the fault resistance is 1000 Ω. A possible reason for the relatively large deviation in that case could be that the actual value of the fault resistance deviates from 1000 Ω.

Applying a series spark gap without any fault resistance gave an unstable arc as shown in Fig. 11. The current in Fig. 11 is strongly distorted. The unstable arc did, however, not have any significant influence on the fundamental harmonic component of the fault current.

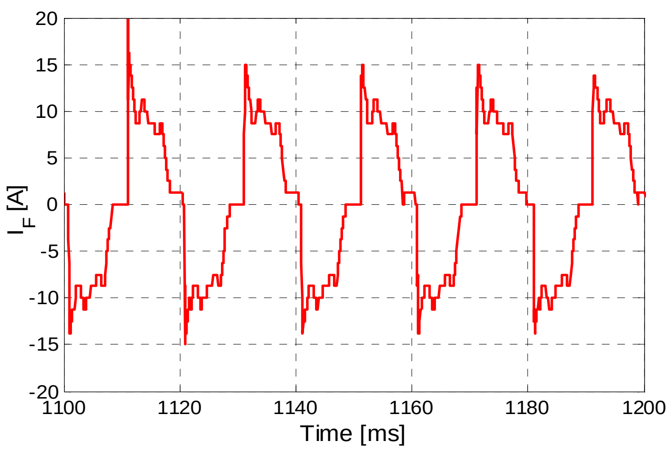


Fig. 11 Measured current faulty feeder when there is a series spark gap and no fault resistance.

VIII. Conclusions

The performed measurements have shown that the non-symmetrical conditions occurring when there is no fault have a strong influence on the zero sequence voltage and currents when the fault resistance is high. The non-symmetrical conditions give in the actual network a current equal 0.26 A when grounding the neutral of the substation transformer. The fault current must then be at least be 1 A to be detected by methods based on phasor variables. The corresponding fault resistance is about 10 kΩ. The non-symmetrical conditions are generally not well known and may vary. The value of the current due to non-symmetrical conditions when there is no fault may therefore be higher than the value obtained from the measurements. A rough estimate is to assume that the maximum value may be twice the value from the measurements. This means that the practical upper limit for resistance in the actual network is reduced from 10 kΩ to 5 kΩ.

The faulty feeder is normally identified by considering the phase between the zero sequence current and voltage. The magnitude of that phase is for the healthy feeders close to but less than 90 deg. The measurements showed that it may exceed 90 deg. due to non-symmetrical conditions. Connecting the resistance in parallel with the arc suppression coil gave a very significant reduction in the phase for the faulty feeder. That reduction makes it much easier to identify the faulty feeder.

The initiation of a single phase to ground fault causes current spikes at least when the fault resistance is low. The measurements showed that fault detection based on the spikes requires a fault resistance less than 1 kΩ.

A comparison between a simplified steady state computational model and the measured zero sequence current of the feeders during the single phase to ground fault gave a deviation within 6 % except for some cases where the deviation was up to 13 %. Those cases were probably due to conditions not included in the computational model. It is in general not realistic to establish a more sophisticated model due to limited knowledge about the required additional input data.

IX. Acknowledgment

The measurements took place in a network belonging to Nord Trøndelag Elektrisitetsverk (NTE) and the authors are grateful for the permission to perform the measurements and their assistance during the measurements.

X. References

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XI. Biographies

Thor Henriksen was born in Trondheim, Norway in 1946. He received the M.Sc. degree in Electrical Engineering from the Norwegian Institute of Technology in 1970, and the Dr.ing. degree in 1973. He is presently working at SINTEF Energy Research as a senior research scientist, mainly in the field of transient studies.

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