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FAULTY FEEDER IDENTIFICATION BASED ON CHARGE-VOLTAGE RELATION

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SUMMARY

A single phase to ground fault in a network that is isolated or grounded by an arc suppression coil causes a rather low fault current and the faulty feeder is traditionally identified from the zero sequence voltage and the sum of the phase currents fed into each feeder from the bus bar. An alternative is proposed in the literature using the charge (i.e. the integral of the current) rather than the current itself for identifying the faulty feeder. The main reason for the proposed approach is that the charge of the healthy feeders is more or less proportional to the instantaneous value of the zero sequence voltage in both transient and steady state conditions. The healthy feeders are identified based on the shape of the charge-voltage curves.

The proposed method has in this paper been applied to measurements from a single phase to ground fault field test. The quality of the measurements was somewhat limited and there was a significant off-set in some of the measured values. A simple numerical selection procedure adapted to the method has been established and applied to the measured values. The procedure does not make any explicit corrections for the off-set but gives in spite of this, satisfactory results as the faulty feeder was identified with a satisfactory safety margin.

A single phase to ground fault is normally detected because it causes some non-symmetrical condition in the network. The non-symmetrical condition in the network without fault limits the possibility of the detecting high impedance faults. This limitation more or less the same for conventional phasor methods as for the method based on charge-voltage relations.

INTRODUCTION

A single phase to ground fault in a network that is isolated or grounded by an arc suppression coil causes a rather low fault current that does not influence the line to line voltages. The faulty feeder connected to the bus bar is traditionally identified from the zero sequence voltage and the sum of the phase currents fed into each feeder from the bus bar. Ref. [1] uses the charge (i.e. the integral of the current) rather than the current itself for identifying the faulty feeder. The main reason for their approach is that the charge of the healthy feeders is more or less proportional to the instantaneous value of the zero sequence voltage and the healthy feeders are identified based on the shape of the charge-voltage curves.

Ref. [1] shows some computation examples and some measurements where the healthy feeders are successfully identified. A reference that presents a method is in principle not necessarily the best way of evaluating the limitations of the proposed method. The method was therefore in this paper applied to some field measurements [2, 3] that were made without considering [1] at all. The quality of the measurements was somewhat limited and there was a significant off-set in some of the measured values.

BASIC IDEA

The basic idea in [1] is here described in detail when there is a steady state single phase to ground fault. The steady state zero sequence impedance of a healthy feeder seen from the bus bar corresponds practically to a pure capacitance and the charge (i.e. the integral of the current) is approximately proportional to the zero sequence voltage. The charge is then a linear function of the instantaneous voltage.

The phase between the current and the voltage is due to losses somewhat less than 90 deg but the deviation from a straight line when plotting the charge as function of the voltage is rather moderate. Fig. 1 shows an example where the phase is 88 deg. Plotting the current as function of the voltage gives an ellipse (or practically a circle with a proper scaling of the axes) as shown in the same figure.

Both the current and the charge can be used to identify a healthy feeder when the network is in steady state. Using the current to identify the faulty feeder during a transient is rather complicated while the charge is as a reasonable approximation proportional to the instantaneous value of the voltage.

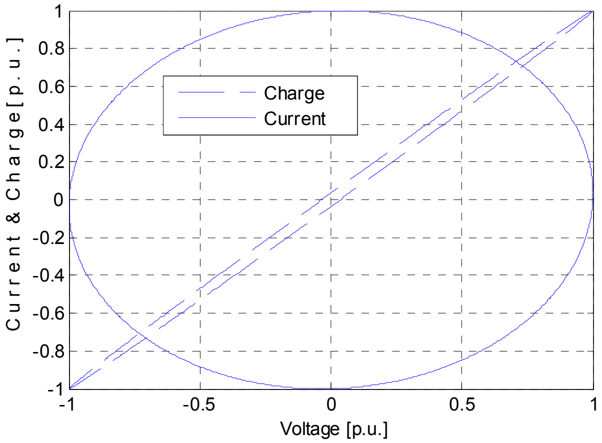

Figure 1 Zero sequence steady state current and charge as function of instantaneous voltage for a healthy feeder.

The deviation from a linear relation increases with increasing length of the involved lines and cables and it is more pronounced when the transients become more significant. The deviation can be analyzed based on models but there are normally some uncertainties about the result mainly due to limited knowledge about the zero sequence parameters. Comparisons with measurements in actual networks are therefore an important supplement. A single phase to ground fault was applied in the measurements in [2, 3] and these measurements are considered to be particularly relevant since the length of the healthy feeders were up to 73 km.

MEASUREMENTS

The measurements took place in a 22 kV radial network that was fed from a 66 kV network via an Yyn transformer. Fig. 2 shows a simplified equivalent circuit diagram where the line voltages are assumed constant. Three feeders (A, B and F) were connected to the bus bar in the substation during the measurements. A ground fault was introduced at the end of the 500 m long feeder F. The length of the two healthy feeders was 48 km (feeder A) and 73 km (feeder B) and a major part of these feeders was overhead lines. The contribution from each healthy feeder to a low impedance single phase to ground fault current is respectively about 12.4 A and 9.3 A. The highest current is obtained for the shortest feeder because it contained somewhat more cables. All together 37 tests were made and 4 were selected for analysis of charge-voltage relation.

Table 1 shows the test conditions for the selected measurements. The results for the two healthy feeders were very similar and the presentation in this paper is limited to feeder A.

Table 1 Fault conditions for the measurements where charge-voltage relation was analyzed.

Fault no.	Fault resistance or spark gap	Arc suppression coil	
		Degree of compensation	Parallel resistance
I	100 Ω	80 %	Connected after 1.7 s
II	Spark gap	100 %	Connected
III	3 kΩ	80 %	Connected
IV	0 Ω	0%	Disconnected

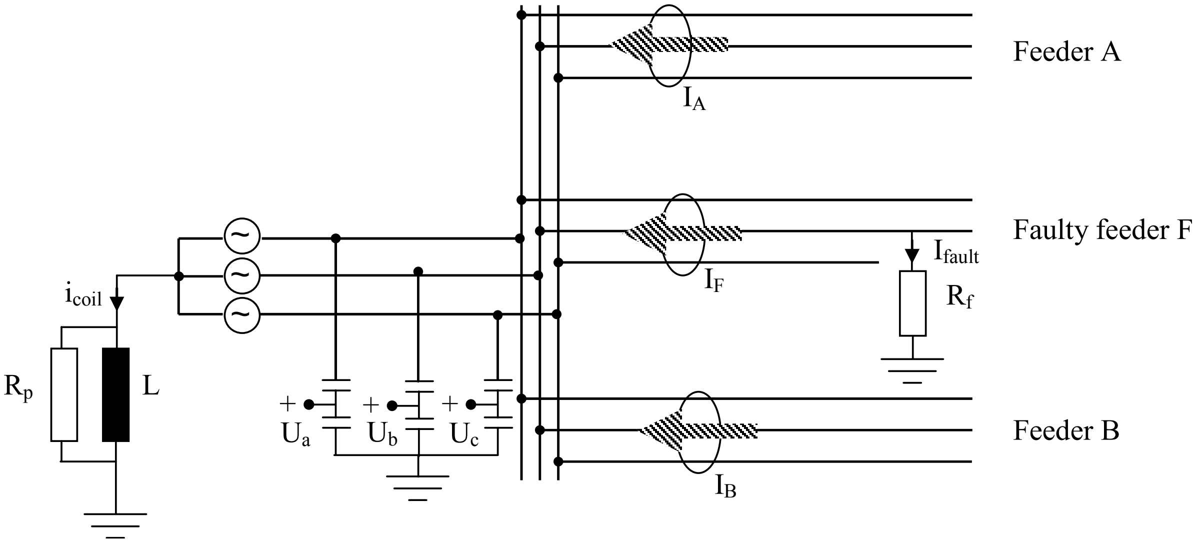

Figure 2 Simplified circuit diagram performed measurements.

Fault no. I – 100 Ω fault resistance, 80 % compensation - fault initiation

The fault resistance is rather low and there was a short time interval with high current spikes in the feeder currents due to the fault initiation. The currents of the faulty feeder and the healthy feeder A are shown in Fig. 3. The initial spikes in Fig. 3 show that there is a significant transient in the current of the healthy feeder. The initial charge-voltage relationships for the healthy feeder A and the faulty feeder are shown in Fig. 4. The time interval used in Fig. 4 is 50 ms and it starts shortly before the fault initiation.

Ref. [1] starts the integration of the current at a zero crossing of the voltage. In this paper the integration is started at a specified time. The effect of this choice is an off-set in the charge. This off-set is not important since it does not influence the shape of a linear charge-voltage relation.

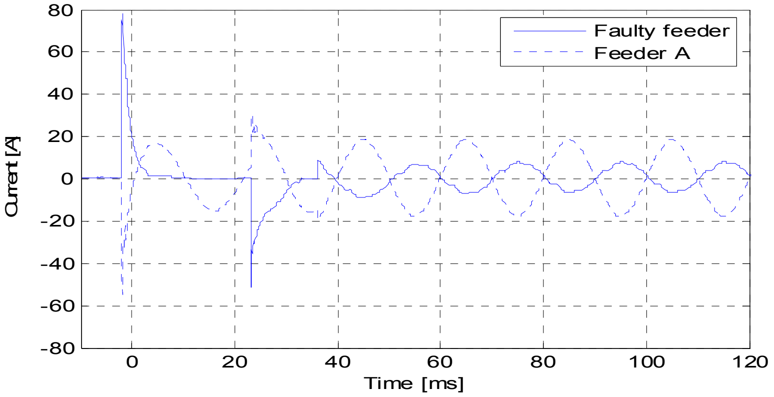

Figure 3 Measured current in faulty feeder and healthy feeder A, fault no. I.

It is in Fig. 4 seen that there is a minor deviation (shown by two arrows) from a linear charge-voltage relation for the healthy feeder. This deviation is, however, insignificant when comparing the shape of the two charge-voltage curves.

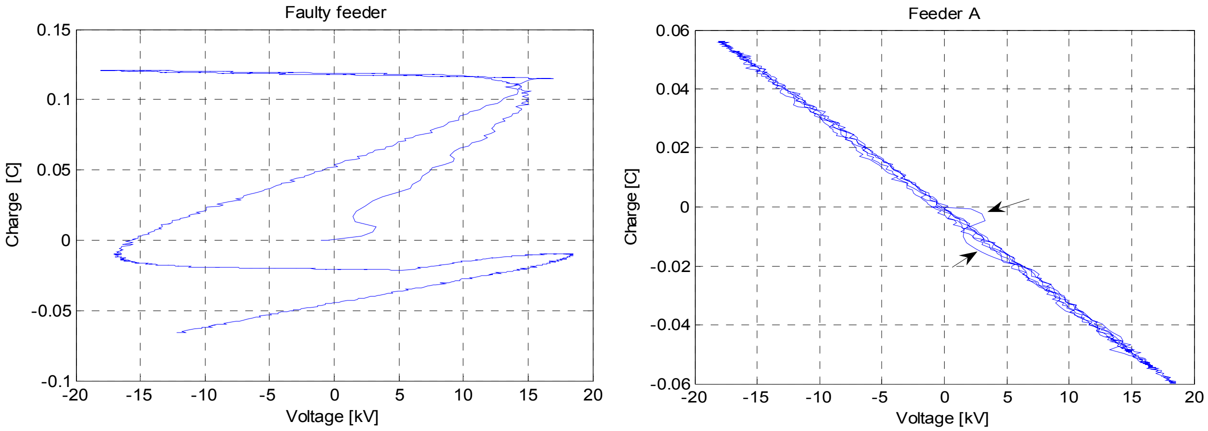

Figure 4 Charge-voltage curves of the faulty feeder covering fault initiation, fault no. I.

Fault no. I – 100 Ω fault resistance, 80 % compensation - connection of parallel resistance

The parallel resistance of the arc suppression coil was connected about 1.7 s after the fault initiation. Fig. 5 shows how the charge-voltage curves are affected by the connection of the parallel resistance. The selected time interval starts about 35 ms prior to the connection of the resistance and ends about 50 ms after the connection. The curve for the faulty feeder shows approximately a transition from one (narrow) ellipse to a new ellipse when connecting the resistance. The curve for the healthy feeder is practically not influenced by the connection of the resistance.

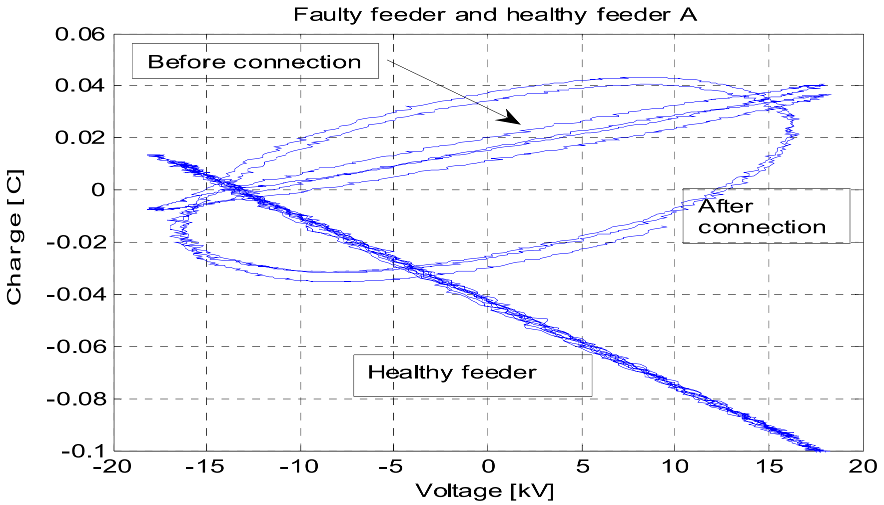

Figure 5 Charge-voltage curves covering connection of parallel resistance, fault no. I.

Fault no. II – Fault with spark gap and distorted fault currents

A spark gap with a gap distance of about 20 mm was used instead of a fault resistance in this measurement. The gap caused multiple extinctions and re-ignitions of the fault current arc and the fault current became strongly distorted as shown in Fig. 6.

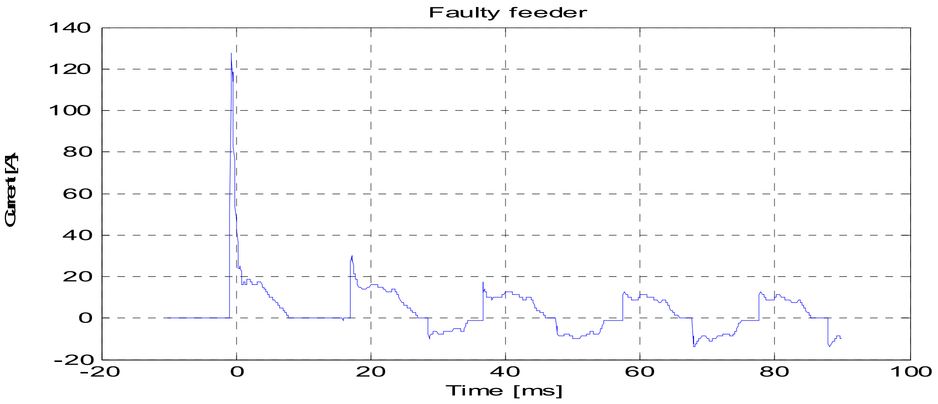

Figure 6 Distorted fault current due to multiple extinctions and re-ignitions, fault no. II.

Fig. 7 shows the charge-voltage relations covering the same time interval as in Fig. 6. The distorted current gives more significant transients than the current shown in Fig. 3 because the 100 Ω resistance was removed and because of the multiple re-ignitions. It is, however, seen that the deviation from a linear charge-voltage relation for the healthy feeder is very little influenced. There is initially a deviation from a linear relationship between charge and voltage. This deviation is a bit stronger than the one observed for fault no. I. The shape of the charge-voltage relation is anyhow significantly different from the relation for the faulty feeder and it is not more difficult to identify the faulty feeder than in Fig. 3. This observation is in line with some measurements presented in [1].

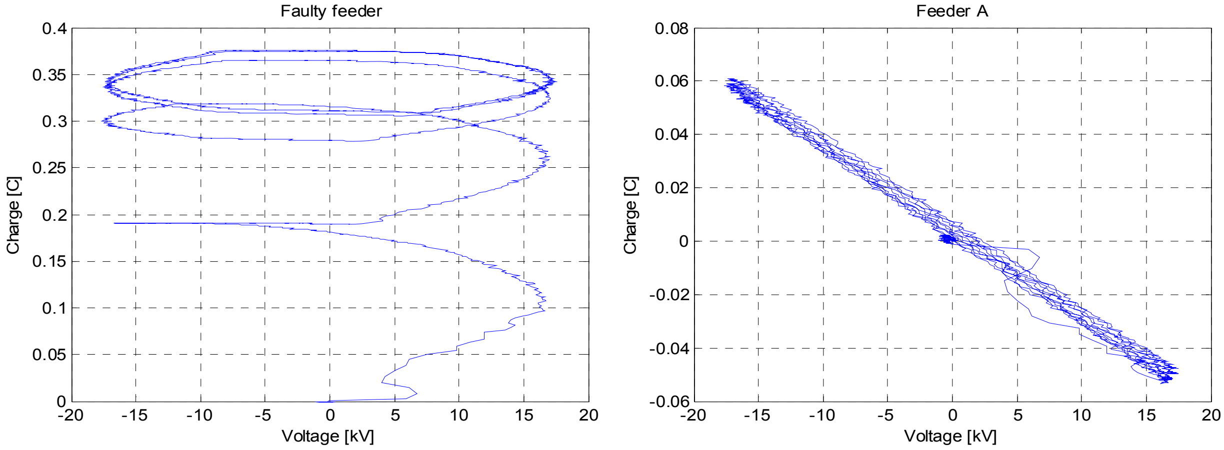

Figure 7 Charge-voltage curves covering period with multiple re-ignitions, fault no. II.

Fault no. III – 3 kΩ fault resistance, parallel resistance connected

The fault resistance was for faults I and II too low to have any significant influence. A high resistance may make it more difficult to detect and to identify the fault, but the fault may still represent a hazard and it is therefore important to identify the faulty feeder. A 3 kΩ fault resistance was introduced in fault no. III and Fig. 8 shows the obtained charge-voltage relation for the faulty feeder and the healthy feeder. The figure covers a 50 ms interval starting shortly before the fault initiation.

The zero sequence voltage varies between ± 18 kV for faults nos. I and II. The corresponding variation for fault no. III is ± 6 kV. The reduction in the zero sequence voltage variation is caused by the relatively high fault resistance.

The result shown in Fig. 8 covers a 50 ms interval and it is seen that curve for the faulty feeder is approaching an ellipse. There is some off-set problem in the measured current and the steady state curve becomes therefore a helix rather than an ellipse. The shape of the steady state part of the curve of the faulty feeder in Fig. 8 is strongly influenced by the resistance connected in parallel with the arc suppression coil.

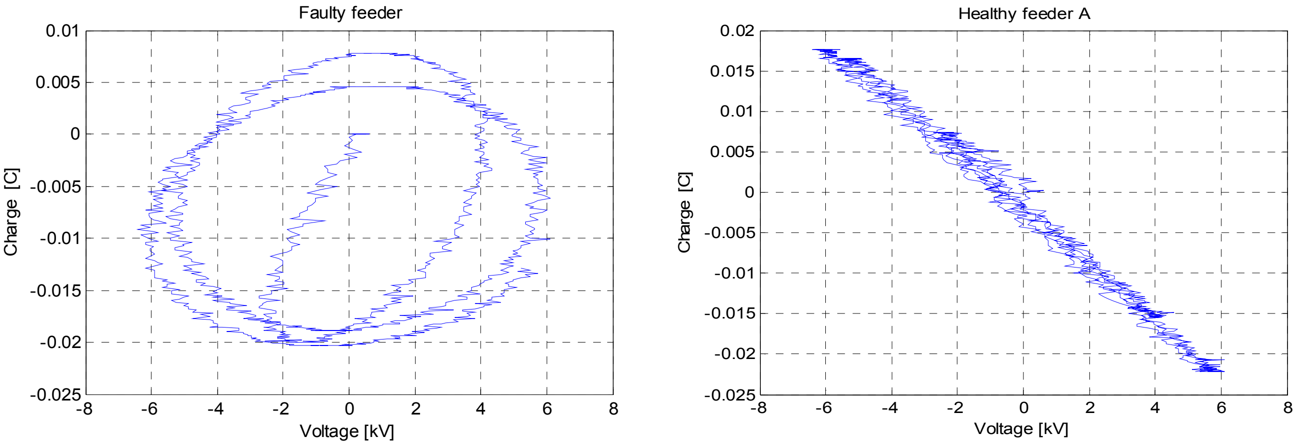

Figure 8 Charge-voltage curves, fault no. III.

A high fault resistance gives less transients and the deviation from the linear relation becomes less for the healthy feeders. This can be seen by comparing Fig. 8 to Figs. 4 and 7. It is clear from Fig. 8 that there is no problem in identifying the faulty feeder when the fault resistance is 3 kΩ and the parallel resistance is connected.

Fault no. IV – Isolated network

The shape of the charge-voltage curve of the faulty feeder is significantly different from the shape obtained for the healthy feeders for the faults presented so far, at least during a transient period. This is not necessarily the case when there is no arc suppression coil and Fig. 9 shows the charge-voltage curves obtained from fault no. IV where the coil and the parallel resistance were disconnected. The curves cover a 30.5 ms interval that starts shortly before the fault initiation.

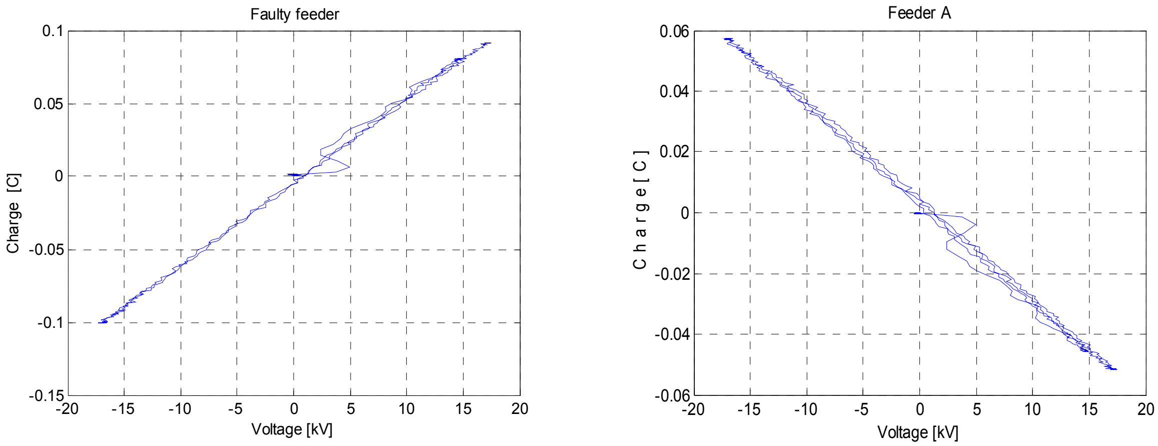

Figure 9 Charge-voltage curves covering fault initiation, fault no. IV.

The curve for the healthy feeder is very similar to the curve obtained from fault no. I. The shape of the curve for the faulty feeder is practically the same as for the healthy feeder except for a change in the sign. The reason for this result is:

- The coil and the parallel resistance are disconnected and the fault current is thus minus the sum of the currents of the healthy feeders

The faulty feeder cannot be identified based on the shape of the charge-voltage curves, but it can be identified based on the sign of the derivative of the charge-voltage relation.

SIMPLE NUMERICAL CRITRTION

The faulty feeder can for all analyzed measurements be identified by a visual inspection of the charge-voltage curves. Such a criterion is not suitable for an automatic identification and a simple numerical criterion was established as an alternative. A sliding 20 ms time interval was introduced and a linear charge-voltage relation was established for each feeder based on least squares. The sum of the square deviations from this linear charge-voltage relation was for all measuring points within the sliding interval computed as base for selecting the faulty feeder. The value of the sum thus obtained for the faulty feeder was at least four times higher than the corresponding value for the healthy feeders. This shows that a criterion based on the sum of the square deviations gives satisfactory results at least for the analyzed measurements.

There was a significant off-set in several of the measured signals, but no correction was introduced before determining the square deviations. This shows that the applied numerical procedure is rather insensitive to the off-set, at least when using a 20 ms sliding time interval.

LIMITATION IN PROPOSED METHOD

Faults with high impedance

The method is based on measured values for the zero sequence voltage and the zero sequence currents. The fault causes a change in the measured variables and the change is reduced when the fault impedance increases. The accuracy (or the sensitivity) of the measuring devices limits the changes that can be observed. The non-symmetrical network conditions are, however, in most cases a far more serious limitation. This problem is not treated in [1] even though they focus on high ohmic earth faults.

The zero sequence current of each healthy feeder is a linear function of the zero sequence voltage:

$$I_0 = Y_0 \cdot U_0 + K_0 \qquad (1)$$

where :

I_0 is the zero sequence current
Y_0 is an equivalent admittance
U_0 is the zero sequence voltage
K_0 is the value of I_0 when U_0 is zero.

The admittance Y_0 corresponds approximately to one third of the total capacitance to ground for the feeder. K_0 is zero when the feeder is symmetrical. K_0 can be computed or measured by imposing $U_0 = 0$. K_0 is strongly dependent on the non-symmetry in the capacitance to ground for the three phases. The phase of K_0 can in practice take any value. The contribution to I_0 from K_0 may therefore be in phase with U_0.

The method in [1] is actually based on (1) with $K_0 = 0$. This means that the fault impedance must be sufficiently low to assure that the change in U_0 due to the fault gives a significantly higher contribution to I_0 than K_0. This limitation is more or less the same as for conventional detection methods based on steady state phasors.

Overcompensated networks

Overcompensation means that the magnitude of the contribution to the fault current from the arc suppression coil is higher than the magnitude of the capacitive fault current. This implies that the phase of the steady state current of the faulty feeder is practically the same as the phase of the currents of the healthy feeders except when there is a resistance in parallel with the coil. The faulty feeder can under such conditions be identified only based on the transients due to the fault initiation. Potential problems due to overcompensation are mentioned but not properly treated in [1]. The performed measurements did unfortunately not include any case with overcompensation.

COMPARISON WITH CONVENTIONAL METHODS

The faulty feeder is normally identified based on the phase of the zero sequence current. Ref. [1] uses as an alternative the shape of the charge-voltage curves. The alternative approach in [1] has in this paper successfully been applied to some field measurements. The faulty feeder was, however, in all the performed measurements correctly disconnected by the conventional ground fault protection too.

The main advantage of the alternative approach seems to be that a simple numerical procedure can be applied to both transients and steady state fault responses. The faulty feeder can then be identified by the initial transients with steady state behaviour as a kind of back-up. It is not possible to distinguish between the steady state response for the faulty feeder and the healthy feeders when the network is overcompensated unless there is a resistance connected in parallel with the arc suppression coil(s). This situation was unfortunately not covered by the performed measurements but it is reason to believe that the faulty feeder can be identified by the transients caused by the fault initiation when using the alternative approach.

CONCLUSIONS

A proposed method in the literature uses the integral of the feeder currents (or charges) as function of the zero sequence voltage to identify the faulty feeder due to a single phase to ground fault. The method has in this report been applied to measurements from a single phase to ground fault field test. The quality of the measurements was somewhat limited and there was a significant off-set in some of the measured values. A simple numerical procedure adapted to the proposed method has been established and applied to the measured values. The procedure does not make any explicit corrections for the off-set but gives in spite of this, satisfactory results as the faulty feeder was identified with a satisfactory safety margin.

The proposed method seems to be equivalent with conventional phasor analysis technique when the faulty feeder can be identified by the steady state fault response. The proposed method has further the potential of identifying the faulty feeder in cases where it cannot be identified from the steady state response.

It is important to identify the faulty feeder even when the fault impedance is high. A single phase to ground fault is normally detected because it causes some non-symmetrical condition in the network. The non-symmetrical conditions in the network without faults limit the possibility of the detecting high impedance faults. This limitation is more or less the same for the conventional phasor methods as for the method based on charge-voltage relations.

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