A METHOD FOR DETECTION AND LOCATION OF HIGH RESISTANCE EARTH FAULTS

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Abstract: A new method is presented for the detection and location of high resistance earth faults in medium voltage distribution networks. The systems considered are with unearthed or compensated neutral and the fault resistances covered in the range 5 .... 160 kohm.

INTRODUCTION

In the first part of the paper, the theory of earth faults in unearthed and compensated power systems is briefly presented. The main factors affecting the high resistance fault detection are outlined and common practices for earth fault protection in present systems are summarized.

A new method for high resistance fault detection and location is then presented. It is based on the change of neutral voltage and zero sequence currents, measured at the high voltage / medium voltage substation and also at the distribution line locations. The performance of the method is analyzed, and the possible error sources discussed. Among these are, for instance, switching actions, thunder storms and heavy snow fall.

The feasibility of the method is then verified by an analysis based both on simulated data, which was derived using an EMTP-ATP simulator, and by real system data recorded during field tests at three substations. For the error source analysis, also some real case data recorded during natural power system events, is used.

EARTH FAULT IN NETWORKS WITH AN UNEARTHED NEUTRAL

In networks with an unearthed neutral, the currents of single phase to ground faults depend mostly on the phase to ground capacitances of the lines. When a fault happens, the capacitance of the faulty phase is bypassed, and the system becomes unsymmetrical (Fig.1). The fault current is composed of the currents flowing through the earth capacitances of the two sound phases.

A model for the fault circuit can most easily be developed using Thevenin's theorem. Before the fault, the voltage at the fault location equals the phase voltage E. The other impedances of the network components are small compared to those of the earth capacitances C_e, and can hence be neglected. For Thevenin's impedance, the earth capacitances are thus connected in parallel, which leads to the model in Fig. 2. In the case where the fault resistance is zero, the fault current can be calculated as follows:

$$I_e = 3\omega C_e E \qquad (1)$$

where $\omega=2\pi f$ is the angular frequency of the network. The composite earth capacitance of the network C_e depends on the types and lengths of the lines connected in the same part of the galvanically connected network. In radially operated medium voltage distribution systems this is, in practice, the area supplied by one HV/MV substation transformer.

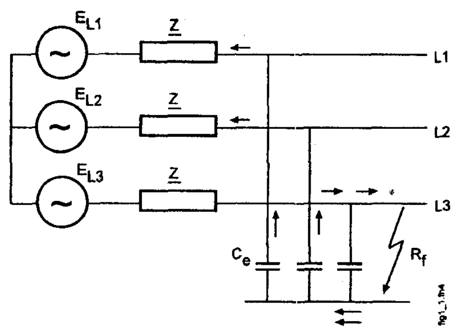

Fig. 1 Earth fault in a network with an unearthed neutral.

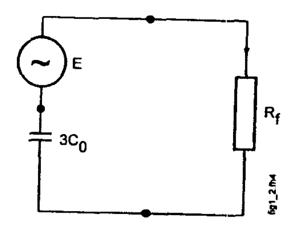

Fig. 2 Equivalent circuit for the earth fault in a network with an unearthed neutral.

IEEE Catalogue No: 98EX137
0-7803-4495-2/98/$10.00 1998 IEEE

In earth faults there is usually some fault resistance R_f involved, the effect of which is to reduce the fault current:

$$I_{ef} = \frac{I_e}{\sqrt{1+(\frac{I_e}{E}\ R_f)^2}} \qquad (2)$$

where I_e is the current obtained from Eq. (1). In unearthed systems the current does not, in practice, depend on the location of the fault. However, the zero sequence current of the faulty feeder, measured at the substation, includes only that part of the current that flows through the capacitances of the parallel sound lines. An interesting question is how the neutral, or zero sequence voltage U_0 acts during the earth fault. According to Fig. 2, this voltage is the same as that which the fault current causes when flowing through the zero sequence capacitances:

$$U_0 = \frac{1}{3\omega C_0} I_{ef} \qquad (3)$$

Using equations (1) and (2) this can also be written in the following form:

$$\frac{U_0}{E} = \frac{1}{\sqrt{1+(3\omega C_0 R_f)^2}} \qquad (4)$$

which states, that the highest value of neutral voltage is equal to the phase voltage. This value is reached when the fault resistance is zero. For higher fault resistances, the zero sequence voltage becomes smaller. In networks with an unearthed neutral, the behavior of the neutral voltage during the earth fault is of extreme importance, since it determines the overall sensitivity of the earth fault protection. Depending on the case, the highest fault resistance that can be detected is typically some thousands of ohms.

NETWORKS WITH A COMPENSATED NEUTRAL

These systems are also known as resonant earthing, or according to the inventor, as Petersen coil systems. The idea of earth fault compensation is to cancel the system earth capacitance by an equal inductance connected to the neutral (Fig. 3), with a corresponding decrease in earth fault currents.

The equivalent circuit for an earth fault in a compensated system, based on Thevenin's theorem, is shown in Fig. 4. The circuit is a parallel resonance circuit and if the reactor is tuned exactly to the system capacitance, the fault current has only a resistive component. This residual current is due to the resistances of the coil and distribution lines together with the system leakage resistances (R_0). Often the earthing equipment is complemented with a parallel resistor R_L, the task of which is to increase the ground fault current in order to make selective relay protection possible.

The residual current is, in medium voltage networks, typically from 5 to 8% of the system's capacitive current. In totally cabled networks the figure is smaller, about 2.3 % [1], whereas in networks with overhead lines solely, it can be as high as 15 % [2]. Using the equivalent circuit of Fig. 4, we can write for the fault current:

$$I_{ef} = \frac{E\ \sqrt{1+R_0^2(3\omega\, C_E - \frac{1}{\omega L})^2}}{\sqrt{(R_f+R_0)^2+R_f^2 R_0^2(3\omega\, C_0 - \frac{1}{\omega L})^2}} \qquad (5)$$

In the case of complete compensation, the above can be simplified as follows:

$$I_{ef} = \frac{E}{R_0 + R_f} \qquad (6)$$

which states, that with full compensation, the earth fault current is determined by phase voltage, fault resistance and the system leakage resistances only.

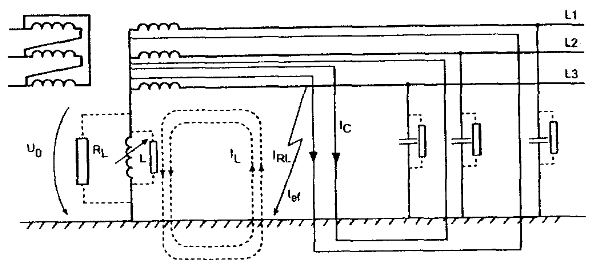

Fig. 3 Earth fault in a network with a compensated neutral. I_C is the current of earth capacitances, I_L is the current of the compensation coil and R_L is the parallel resistor used for increasing the fault current.

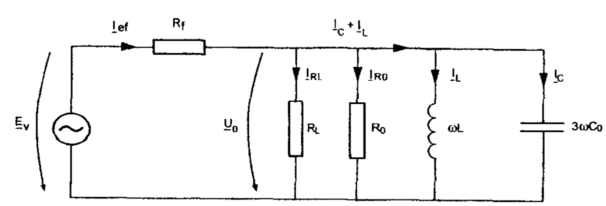

Fig. 4 Equivalent circuit for the earth fault in a network with a compensated neutral.

The neutral voltage U_0 can be calculated correspondingly:

$$U_0 = \frac{I_{ef}}{\sqrt{(\frac{1}{R_0})^2 + (3\omega C_0 - \frac{1}{\omega L})^2}} \quad (7)$$

which in the case of complete compensation, is reduced to the following form:

$$\frac{U_0}{E} = \frac{R_0}{R_0 + R_f} \quad (8)$$

For the above equations it was assumed that no additional neutral resistor R_L is used. If needed, the effect of R_L can be taken into account by replacing R_0 in equations (5) to (8) by the parallel coupling of R_0 and R_L.

As in the case with an unearthed neutral, the highest zero sequence voltage equals the phase voltage of the system. During earth faults, the neutral voltages are substantially higher in the systems with a compensated neutral than in the case with an unearthed one. Hence a more sensitive relay protection for high resistance faults can be gained in the former case.

PRESENT TECHNIQUES FOR EARTH FAULT DETECTION

In this section, the present practices for earth fault detection in high impedance earthed systems are outlined. The techniques discussed are directional earth fault relays and neutral voltage relays.

Earth fault protection of MV feeders

The best result for earth fault protection of MV lines in high impedance earthed systems is gained if directional relays are used. In networks with an unearthed neutral, the phase shift between the earth fault current of the faulty line and the current at the sound lines is about 180^0. Hence, the selectivity is based on the measurement principle whereas the relay settings, neutral voltage and zero sequence current, primarily affect the sensitivity of the protection only. In this case, the tripping is permitted, if the following conditions are met:

- the zero sequence current I_0 exceeds the setting, and
- the neutral voltage U_0 exceeds the setting, and
- the phase shift between I_0 and U_0 is in the range $\varphi_0 \pm \varphi\Delta$ (where $\varphi_0 = 90^0$ and $\Delta\varphi = \pm 80^0$)

A more modern characteristic is the reactive current measurement, which is met in numerical relays. In this case the tripping is initiated, if neutral voltage and reactive current $I\sin\varphi$ both exceed the threshold value. However, in unearthed systems, there is practically no difference between the performance of the two relay characteristics, since the phase angle of the neutral voltage compared to the sum current is usually fairly close to -90^0.

In resonant earthed systems, the protection can not be based on the reactive current measurement, since the current of the compensation coil would disturb the operation of the relays. In this case, the selectivity can be based on the measurement of the active current component. Often the magnitude of this component is very small, and must be increased by means of a parallel resistor in the compensation equipment. The typical characteristics of the directional relays for compensated systems are similar to those used in unearthed networks. The only difference is that the characteristics are turned by -90^0.

Table 1. The sensitivity of earth fault detection based on the zero sequence overvoltage relay. A system with a compensated neutral. U is the nominal voltage, I_c is the capacitive fault current after compensation, I_r is the resistive current of the system and R_f is the fault resistance value for which a fault can be detected [3].

U (kV)	I_c (A)	I_r (A)	R_f (kohm)
6.6	5	5	13
11	5	5	22
22	10	10	22
33	20	10	24
44	20	10	32
55	20	10	40

The use of zero sequence overvoltage relays

In high impedance earthed systems, the neutral voltage caused by an earth fault is practically the same in the whole supply area of the substation transformer. Also, its magnitude does not depend on the location of the fault. Consequently, a general detection of earth faults can be gained by means of a zero sequence overvoltage relay.

In overhead line networks, faults with very high resistance can appear due to trees leaning against a conductor, for instance. These faults tend to evolve gradually into a fully established earth fault. Hence, an indication of such a fault would be of very high importance. The sensitive detection of high impedance earth faults can, into some degree, be achieved by means of neutral voltage relays. In this case, the voltage threshold value taken is as low as it is possible. The lowest limit depends on the neutral voltage present during the normal operating state. In unearthed systems this usually is very small, typically around 1% of the nominal phase voltage, whereas in completely compensated networks higher values are encountered. In the latter case, the neutral voltage can be kept low by careful transposing of lines and by an appropriate setting of the compensation reactor. If the normal value varies below 2%, a recommended relay setting is 3%. In addition, a long time delay, up to 5 minutes, is needed. According to Reference

[3], these settings allow for the fault detection sensitivity given in Table 1. It should be noted, however, that the settings in the example are applicable for alarm only.

The typical resistance of a tree is in the range 20 ... 80 kΩ. These figures apply in the seasons when the earth is not frozen. In the winter time much higher resistances, ranging up to several hundreds of kohms are encountered. As can be noticed from Table 1, most faults of this type are beyond the reach of the zero sequence overvoltage relays.

A NEW METHOD FOR HIGH RESISTANCE FAULT DETECTION

A new method for high resistance fault detection and location, based on the change of neutral voltage and zero sequence currents, is presented in this section. The practical implementation of the method requires a close integration of the substation SCADA with modern relays which are designed to be used for protection and control of distribution network. A close connection is needed to the remote terminal units in the line locations as well (Fig. 5).

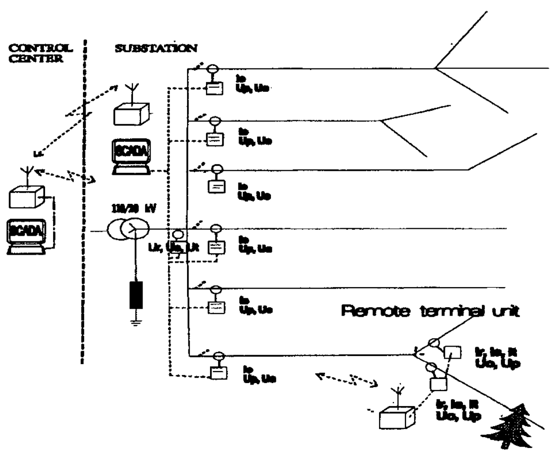

Fig 5. The high resistance fault detection and location system.

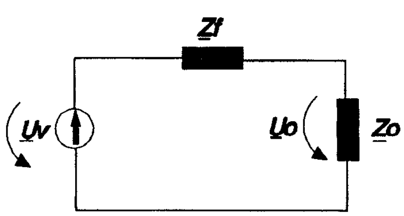

Fig.6 Simplified equivalent circuit for an earth fault in a distribution network

Neutral voltage analysis

The method for earth fault detection can be explained by the simplified equivalent circuit for the one-phase earth fault (Fig. 6). Using the equivalent circuit, the fault impedance Z_f can be determined in terms of the measured voltages and the zero-sequence impedance of the network as follows:

$$\underline{Z}_f = \left(\frac{\underline{U}_v}{\underline{U}_0} - 1\right) * \underline{Z}_0 \tag{9}$$

where $\underline{Z}_0$ is the zero-sequence impedance of the network (Fig. 7), $\underline{Z}_f$ is the fault impedance, $\underline{U}_v$ is positive-sequence component of the phase to earth voltage and $\underline{U}_0$ is neutral voltage. $\underline{Z}_0$ can be determined from the equivalent circuit of Fig.7. In the unearthed network (Fig. 7a) it is the parallel connection of the phase-to-ground capacitances and phase-to-ground resistances, so called "leakage resistances". The total phase-to-ground capacitance 3Ce depends on the "live" length of the feeders of the system. For systems earthed via a Petersen coil it is necessary to take into account also the coil, and the circuit must be complemented with parallel connection of the coil impedance, Fig 7b.

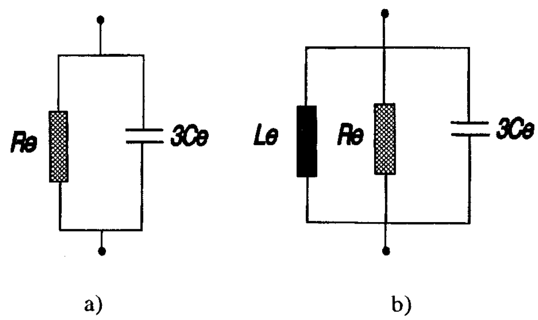

Fig 7. Equivalent circuit of the zero-sequence network for the unearthed system (7a) and for the compensated system (7b).

For the detection of the high resistance earth fault it is essential to determine the resistive part of the fault impedance. In Eq.9. U_o represents the phasor sum of the phase voltages and U_v is the positive sequence component of the phase voltage, measured at the moment considered. Applying Eq. 9 for three times and using the following values of U_v, the faulted phase can also be determined:

$$\begin{aligned} &1) \quad \underline{U}_v \angle \underline{\varphi} \\ &2) \quad \underline{U}_v \angle \underline{\varphi + 120^\circ} \\ &3) \quad \underline{U}_v \angle \underline{\varphi + 240^\circ} \end{aligned} \tag{10}$$

From the calculated three values of Z_f, the resistive part shows the highest value in the faulted phase. Because the fault impedance must be resistive, the calculated resistive parts of Z_f for the other two "healthy" phases are negative.

The triggering level of the algorithm is set so, that a high resistive earth fault is indicated, if the calculated maximum real part of Z_f is at least four times the magnitude of the imaginary part of the corresponding Z_f.

The detection of very high fault resistances is difficult due to the neutral voltage present in the normal network conditions. This is mainly caused the natural unbalances of the feeders. The sensitivity of the method can be improved by using for $\underline{U}_0$ the change of the neutral voltage, determined as a difference of the neutral voltage at the moment considered and the corresponding mean value of the last ten minutes.

After calculation of the fault resistance the residual current can also be determined using the equivalent circuit of Fig. 6. When combining this information to the knowledge about the faulty phase, a very powerful means for detecting the faulty feeder, and further the faulty branch of the line, can be implemented.

Table 2. Experimental results obtained by the neutral voltage algorithm.

Staged fault		Lammi		Maalahti		Kitee	
R_f kΩ	Ph.	R_f kΩ	Angle deg.	R_f kΩ	Angle deg.	R_f kΩ	Angle deg.
20	L1	15.9	8.6	20.5	11.3	17.0	-7.2
40	L2	39.8	7.6	41.7	2.1	26.4	-10.1
60	L3	71.2	1.8	62.2	10.5	46.8	-2.9
80	L2	83.0	7.6	80.5	-1.1	50.2	-10.1
100	L1	111.8	6.9	131.3	5.5	81.5	-14.8
160	L3	179.5	-7.6	120.0	18.7	142.4	-3.0
180	L3	177.0	-33.6	141.6	17.2	156.6	-0.9
220	L3	178.1	-40.6	223.3	27.0	194.4	-2.4
Tree	L1	174.4	9.4	-	-	-	-
Tree	L1	207.1	7.0	-	-	-	-
Tree	L2	281.9	33.3	-	-	-	-
Tree	L3	237.8	-32.0	-	-	-	-

FEASIBILITY OF THE METHOD AND ERROR SOURCES

In order to expose the presented algorithm to a wide range of field conditions, it was tested with naturally occurring faults, intermittent disturbances, staged faults and normal system activity. The feasibility of the method was also verified by an analysis based on simulated data, which was derived using an EMTP-ATP based network model [4]. In the simulations, the sampling rate was 500 Hz and the sampling period was one second. Using simulated data, earth faults up to 500 kΩ could be detected. In order to evaluate the accuracy of the algorithm, we must keep in mind, that the simulated data did not include error factors. Among these are the noise of the measured quantities, produced by the power system itself, the accuracy of the measurement transducers, the properties of the electrical circuits of the measuring system and so on [5].

The field tests with staged faults were carried out in the normal network conditions at the Lammi substation of Häme Electricity and at the Maalahti substation of Vaasa Electricity, where the distribution networks are unearthed and at the Kitee substation in North-Carelian Electricity, where the network is compensated. The networks are mainly of overhead construction. Tables 2...4 show some results of the earth fault test.

Table 3. Changes of residual currents in the beginning of the feeders at the Kitee substation and at the disconnector location. Faulted feeder is marked in bold.

Staged fault		Substation					Disc.
Rf kΩ	Ph.	Io1 (A)	**Io2 (A)**	Io2 (A)	Io4 (A)	Io5 (A)	Io (A)
20	L1	0.284	**0.467**	0.227	0.599	0.569	**0.106**
40	L3	0.157	**0.421**	0.149	0.384	0.390	**0.076**
60	L2	0.108	**0.284**	0.091	0.248	0.239	**0.047**
80	L3	0.082	**0.152**	0.062	0.175	0.170	**0.033**
100	L2	0.054	**0.105**	0.069	0.182	0.178	**0.030**
120	L3	0.045	**0.069**	0.042	0.109	0.097	**0.018**
160	L1	0.010	**0.093**	0.043	0.137	0.139	**0.030**
180	L2	0.039	**0.036**	0.047	0.134	0.127	**0.028**
200	L1	0.034	**0.063**	0.047	0.125	0.110	**0.014**
220	L1	0.021	**0.049**	0.025	0.057	0.055	**0.023**

Table 4. Some experimental results for detection of the faulted feeder in compensated network obtained by the residual current algorithm. Faulted feeder is marked in bold.

Staged fault		Substation					
Rf kΩ	Ph.	Io1 (A)	**Io2 (A)**	Io2 (A)	Io4 (A)	Io5 (A)	Uo (V)
20	L1	0.047	**0.561**	0.010	0.019	0.017	1350
40	L3	0.053	**0.545**	0.019	0.047	0.056	866
60	L2	0.029	**0.345**	0.056	0.025	0.027	574
80	L3	0.036	**0.191**	0.006	0.015	0.014	422
100	L2	0.015	**0.197**	0.012	0.034	0.032	365
120	L3	0.010	**0.095**	0.007	0.027	0.018	242
160	L1	0.027	**0.157**	0.010	0.026	0.028	201
180	L2	0.035	**0.114**	0.022	0.064	0.061	204
200	L1	0.050	**0.120**	0.026	0.069	0.059	154
220	L1	0.006	**0.072**	0.005	0.003	0.001	130

Table 5. Fault resistances detected by neutral voltage algorithm before the fault developed to a permanent one.

Substation	Fault cause	R_f / kΩ
Honkavaara	Broken insulator	20.0
Honkavaara	Broken insulator	108.0
Honkavaara	Broken insulator	110.0
Honkavaara	Transformer fault	29.8
Honkavaara	Snow burden	29.2
Honkavaara	Snow burden	104.0
Kitee	Downed conductor	228.0
Lammi	Downed conductor	223.0
Renko	Tree contact	95.5

Table 6. Fault resistances detected by neutral voltage algorithm in the case of some intermittent disturbances in the network.

	Unearthed network			Compensated network		
	$R_{f,min}$ kΩ	$R_{f,max}$ kΩ	$R_{f,mean}$ kΩ	$R_{f,min}$ kΩ	$R_{f,max}$ kΩ	$R_{f,mean}$ kΩ
Switching action	43	199	93	10	218	53
Thunder storm	85	116	93	-	-	-
Snowfall	199	268	233	46	318	136

Table 2 shows the fault resistances determined by neutral voltage algorithm from the field measurements at three substations and in Table 5 is expressed some corresponding values for the real case faults before they developed to a permanent fault. Especially in the compensated network, residual currents of the feeders are very low in the case of high resistance earth faults. Table 3 shows the measured changes of the residual currents in the beginning of the feeders at the Kitee substation and at the disconnector location. Faulty feeder is marked in bold. In Table 4 is expressed some experimental results for detection of the faulty feeder in compensated network obtained by the residual current algorithm. Our experience showed that the algorithm was able to detect resistive earth faults up to a resistance of 160 kΩ in a 20 kV distribution system.

The drawback is that the normal system activity and intermittent disturbances cause similar changes to neutral voltage and residual currents as the real faults in the feeders. Table 6 shows the calculated resistances which correspond to the recorded changes of the neutral voltages in the case of normal switching actions, thunderstorm and snowfall. These results are based on the continuous monitoring and recording of the neutral voltages at four substations during the period of one and a half year. For discrimination of the intermittent disturbances, the algorithms use one second mean values of the currents and voltages, and for calculations of the corresponding changes, mean values of the last ten minutes are used as a reference level. Snowfall and thunder storn can be identified by the fact, that their effect is seen in several feeder current measurements at the same time. The switching actions, in turn, can be discriminated by the phase angle of the fault impedance computed by the algorithm. In addition, also real-time information of the network connectivity changes, obtained from the SCADA and network automation systems, can be used.

CONCLUSIONS

A new method was presented for the single phase to earth fault detection and location in high impedance earthed distribution systems. The method is able to detect faults up to 160 kohms. The drawback of the method is that the normal system activity and intermittent disturbances may cause similar changes to neutral voltage and residual currents as the real faults in the feeders. Examples of these cases are normal switching actions, thunderstorm and snowfall. This problem can be mitigated by using longer time average measurements for comparison when identifying the faulty feeder or line section and by a proper integration of the automation systems, including protective relays, substation SCADA and network automation.

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