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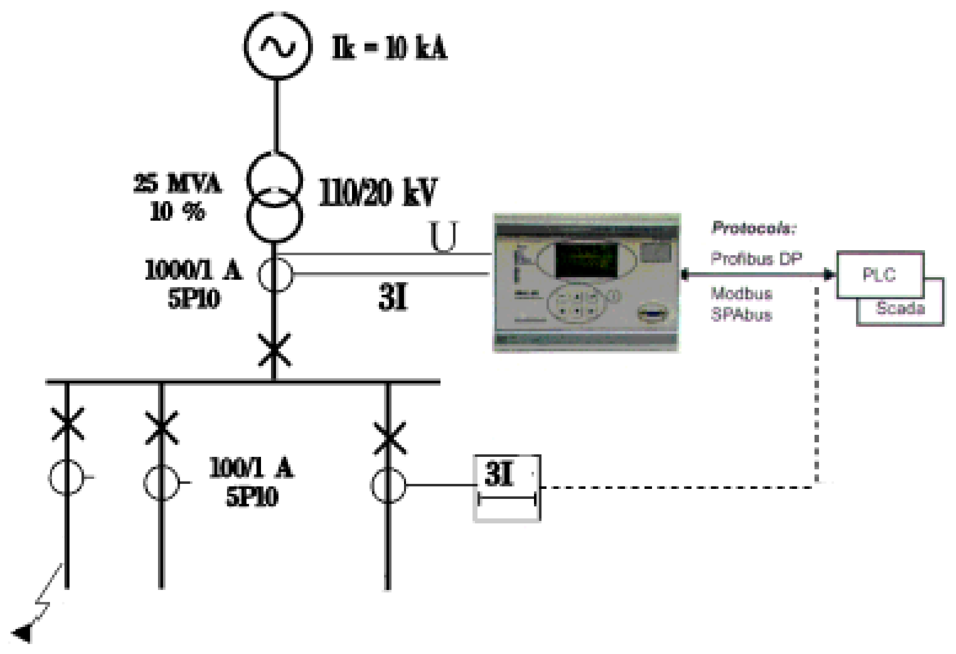

Seppo Hänninen & Matti Lehtonen

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Abstract

This report describes three novel methods for earth fault location in unearthed, compensated and low-resistance grounded networks. In Finland, the medium voltage, 20 kV, distribution networks are either unearthed or compensated. Therefore, the last mentioned algorithm is primarily intended for the export industry of the Finnish relay manufacturers. The developed algorithms are based on the use of fundamental frequency signals, and they need only one measurement unit per primary transformer at the substation. This is due to the fact that the fault current can be determined from the negative sequence component of the measured signal in the supply bay. The scope is restricted to radially operated systems. The earth fault distance location is based on the line impedance calculation in these algorithms.

For fault location in unearthed and resistance grounded networks, three different measurements are needed, which are spaced in time: pre-fault, fault and post-fault. In a compensated network, however, only two measurements are needed during an earth fault.

The soundness of the algorithms was tested using simulated data. According to the results, the performance of the methods is good enough for practical use, and most likely the accuracy is comparable to transient based methods. The algorithms were tested when the faulty feeder was both loaded and unloaded, with 10 – 30 Ω fault resistances. The error in distance computation was about 1- 2 km, depending on the loading and the fault resistance value.

Preface

The subject of this research note is earth fault distance estimation in unearthed, compensated and low resistance grounded networks. The work is a consequence of several years' research and development work at VTT Processes, concerning the earth fault problems in medium voltage electrical distribution networks. The work reported in this note was mainly carried out in the project: "Earth fault distance computation" during the year 2002, and it belongs to the national technology programme TESLA on Information Technology and Electric Power Systems. The aim of the project in the technology programme was to develop new applications for fault management in distribution automation and to decrease outages times.

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Espoo, June 2002

Seppo Hänninen Matti Lehtonen

Contents

List of symbols

ANN	artificial neural network
ATP-EMTP	alternative transients program - electromagnetic transients program
HV/MV	high voltage/medium voltage
L1, L2, L3	phases of the symmetrical three phase system
MEK	mean absolute error in kilometres
R, S, T	phases of the symmetrical three phase system
R1, S1, T1	pre-fault measurement
R2, S2, T2	fault measurement
R3, S3, T3	post-fault measurement
SCADA	supervision control and data acquisition
1, 2, 0	positive, negative and zero sequence

C	capacitance
C_e	phase-to-ground capacitance of the unearthed network
C_o	zero-sequence capacitance
E	voltage (source), phase voltage
f	frequency
I	current
$\underline{I}_C$	capacitive current
$\underline{I}_{CE1,CE2,CE3}$	phase to ground capacitive currents
$\underline{I}_e$	earth fault current
$\underline{I}_{ef}$	earth fault current reduced by fault resistance
$\underline{I}_f$	fault current
$\underline{I}_L$	load current
$\underline{I}_l$	current of suppression coil
$Im[f(t)]$	imaginary part of function
$\underline{I}_P$	current of the parallel resistor
$\underline{I}_{sf}$	is the phase current during the fault including the fault and load current
$\underline{I}'_{sf}$	is the current through the line after the tap and is equal to I_{sf}-I_{tapf}
$\underline{I}_{tapf}$	is the current through the tap after the fault
$\underline{I}_{1,2,0}$	positive, negative and zero sequence current
j	integer
k	load current distribution factor
L	inductance
m	is the per unit distance between the source and the fault and is equal $p+n$
n	is the per unit distance between the tap and the fault
p	is the per unit distance between the source and the tap
R	resistance

Re	earthing resistor
R_f	fault resistance
R_{LE}	phase-to-ground resistance of the system
R_P	parallel resistor
s	distance
U	voltage
U_o	neutral voltage
$\underline{U}_L$	phase voltage
$\underline{U}_{L1,L2,L3}$	phase-to-ground voltages
$\underline{U}_{vn}$	nominal value of phase voltage
$\underline{U}_{1,2,0}$	positive, negative and zero sequence voltages
$\underline{X}_{1C,2C,0C}$	positive, negative and zero sequence capacitive reactances
$\underline{X}_{1l,2l,0l}$	positive, negative and zero sequence line reactances
$\underline{Z}$	impedance
$\underline{Z}_{1,2,0}$	positive, negative and zero sequence impedances
$\underline{Z}_e$	earthing impedance
$\underline{Z}_f$	fault impedance
$\underline{Z}_L$	impedance of the line
$\underline{Z}_T$	impedance of the transformer
$\underline{Z}_{tap}$	is the lumped impedance of the tap
ω	angular frequency
φ_{Lf}	angle between the load and fault current phasors

1. Introduction

The difficulty with the accurate location of ground faults in high impedance grounded networks is that the fundamental frequency fault currents are often small compared to the load currents, even when the fault resistances are very small. Until now, the use of fundamental frequency components has worked only in meshed operation, or when it has been possible to connect the faulty feeder into a closed ring with one healthy feeder (Winter 1993, Roman & Druml 1999, Nikander 2002).

The most promising methods for earth fault distance computation developed so far for radial systems are based on the use of earth fault initial transients. This is due to the fact that the charge transient component can easily be distinguished from the fundamental frequency load currents. It has, in many cases, a higher amplitude than the steady state fault current. For the time being, the practical implementation of the transient based methods to numerical relays is restricted by the high sampling rate of 5-10 kHz that is needed. The other drawback is that the practical implementation of the aforementioned methods requires the measurement of the current and voltage on all three phases of the outgoing feeders. Especially at old but still active substations, the retrofitting of an automation function for earth fault distance computation is expensive to implement, because it requires modern numerical relays on each outgoing feeder.

In Finland, medium voltage distribution networks are unearthed (80 %) or compensated (20 %) (Nikander & Lakervi 1997). However, in other countries it is usual that the networks use different types of impedance earthing. This report describes three novel methods for earth fault location in unearthed, compensated and low-resistance earthed networks. The last mentioned algorithm is intended for the export industry of the Finnish relay manufacturers. The developed algorithms are based on the use of fundamental frequency signals, and require only one measurement unit per primary transformer at the substation. The scope is restricted to radially operated systems.

In this report, the following definitions are used. The term high impedance grounding is used to differentiate between resistance and solid grounding. In practice this means either an ungrounded system where the insulation between neutral and ground is of the same order as the phase insulation, or a compensated neutral system where the neutral point is earthed by a suppression coil in order to reduce the fault current. The supply bay is located between the primary transformer and feeder cubicles at the substation, and through it the entire electrical energy flows from the primary transformer to the busbar and on to the outgoing feeders. Low resistance fault means that the value of the fault resistance is 50 Ω or smaller. Fault location means the determination of the faulty feeder or line section. Fault location is also used as a general term when discussing fault distance computation. In fault distance computation, the issue is the shortest feeder length from substation to fault position. This does not imply exact knowledge of the fault point, since if the feeder has many laterals, several possible fault points may be obtained. The actual fault location can be determined from these candidate locations by some other means, such as fault indicators or by trial and error.

This research note is organised as follows. First we discuss the basic properties of high impedance grounded networks and the calculation of currents and voltages during an earth fault. In chapter 3, the existing methods for earth fault distance estimation are reviewed, based both on the initial transients and on the fundamental frequency signals. In chapter 4, the main features of the supply bay measurements are outlined. In chapters 5-7, three novel methods are proposed for fault distance estimation in the case of low resistance faults in unearthed, compensated and resistance earthed networks. The methods are based on the calculation of the line terminal impedance, and are evaluated using simulated test data.

2. An earth fault in a high impedance grounded network

The way in which the neutral is connected to earth determines the behaviour of a power system during a single phase to ground fault. From the safety point of view, the earth fault current causes a hazard voltage between the structure of the faulted equipment and earth. In this chapter, the basic properties of unearthed, compensated and high resistance earthed networks are discussed, with special attention given to the calculation of currents and voltages during a fault.

2.1 Networks with an unearthed neutral

Ungrounded systems have no intentional direct grounding but are grounded by the natural capacitance of the system, see Fig. 1 (Blackburn 1993). The currents in single phase to ground faults are low and depend mostly on the phase to ground capacitances of the lines. The voltage between faulted equipment and earth is small, which improves safety. On the other hand, transient and power-frequency overvoltages can be higher than those obtained, for example, with resistance earthed systems (Lakervi & Holmes 1995). When a fault occurs, the capacitance of the faulty phase is bypassed, and the system becomes unsymmetrical. 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. This leads to the model in Fig. 2.

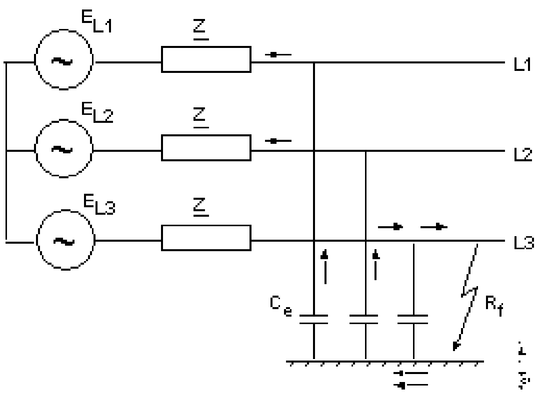

Figure 1. Earth fault in a network with an unearthed neutral (Lehtonen & Hakola 1996)

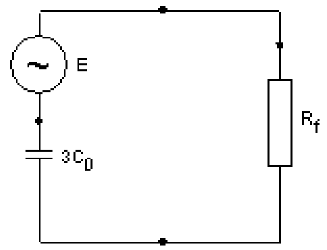

Figure 2. Equivalent circuit for an earth fault in a network with an unearthed neutral (Lehtonen & Hakola 1996)

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.

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

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

where I_e is the current obtained from eq. (1). In unearthed systems this 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. This causes problems in the selective location of faults by the protective relaying. The zero sequence voltage U_0 is the same as that caused by the fault current when flowing through the zero sequence capacitances:

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

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

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

which states that the highest value of the 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 the case of a phase to ground fault with zero fault impedance, the unfaulted phase to ground voltages are, in effect, increased by $\sqrt{3}$, as shown in Fig. 3. Its maximum value is about 1.05U (U = line-to-line voltage) when the fault resistance is about 37% of the impedance consisting of the network earth capacitances. These systems require line voltage insulation between phase and earth (Klockhaus et al 1981). In a normal balanced system the phase to neutral voltages and phase to ground voltages are essentially the same, but in the case of an earth fault, they are quite different. The neutral shift is equal to the zero sequence voltage. In networks with an unearthed neutral, the behaviour of the neutral voltage during an earth fault is of extreme importance, since it determines the overall sensitivity of the fault detection.

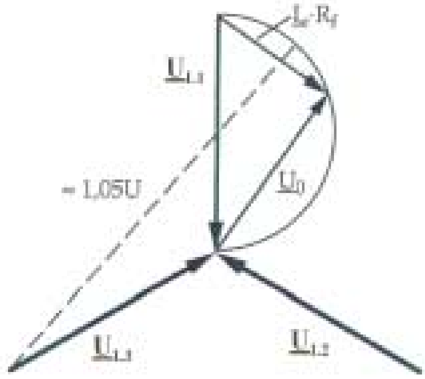

Figure 3. Voltages during an earth fault in an unearthed network (Mörsky 1992).

2.2 Networks with a compensated neutral

The idea of earth fault compensation is to cancel the system earth capacitance by an equal inductance, a so-called Petersen coil connected to the neutral, which results in a corresponding decrease in earth fault currents, see Figs 4 and 5. The equivalent circuit for this arrangement is shown in Fig. 6. Instead of one large controlled coil at the HV/MV substation, in rural networks it is possible to place inexpensive small compensation equipment, each comprising a star-point transformer and arc-suppression coil with no automatic control, around the system. With this system the uncompensated residual current remains somewhat higher than in automatically tuned compensation systems (Lakervi & Holmes 1995).

In Fig. 4, the circuit is a parallel resonance circuit and if exactly tuned, the fault current has only a resistive component. This is due to the resistances of the coil and distribution lines together with the system leakage resistances (R_{LE}). Often the earthing equipment is complemented with a parallel resistor R_p, the task of which is to increase the ground fault current in order to make selective relay protection possible.

The resistive 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 to 3% (Hubensteiner 1989), whereas in networks with overhead lines solely, it can be as high as 15% (Claudelin 1991).

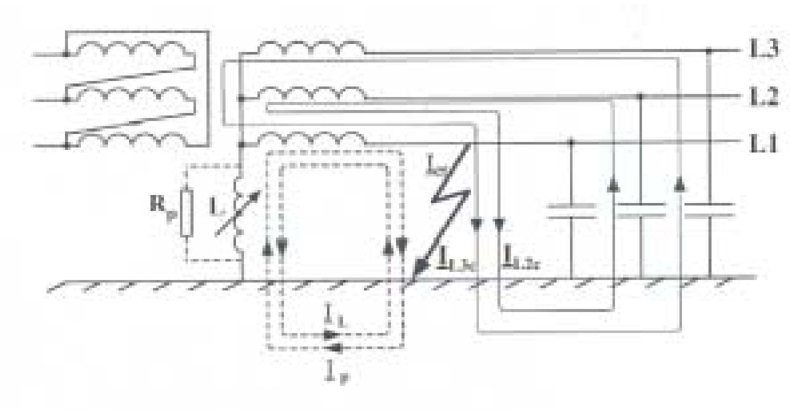

Figure 4. Earth fault in a network with a compensated neutral. $\underline{I}_t$=$\underline{I}_L$-$\underline{I}_P$ is the current of the suppression coil and a parallel resistor, $\underline{I}_{L2c}$ and $\underline{I}_{L3c}$ are the capacitive currents of the sound phases, and $\underline{I}_{ef}$=$\underline{I}_{L2c}$+$\underline{I}_{L3c}$-$\underline{I}_t$ is the earth fault current at the fault point (Mörsky, 1992).

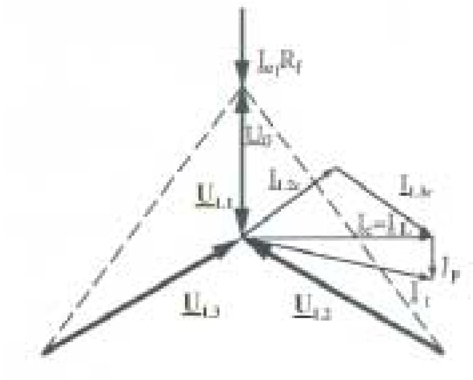

Figure 5. The phasor diagram of currents and voltages in the case of an earth fault in a fully compensated system. $\underline{I}_C$=$\underline{I}_{L2c}$+$\underline{I}_{L3c}$ is the current of earth capacitances, $\underline{I}_t$=$\underline{I}_L$-$\underline{I}_P$ is the current of the suppression coil and a parallel resistor, $\underline{I}_{ef}$=$\underline{I}_c$-$\underline{I}_t$=$\underline{I}_P$ is the earth fault current (Mörsky 1992).

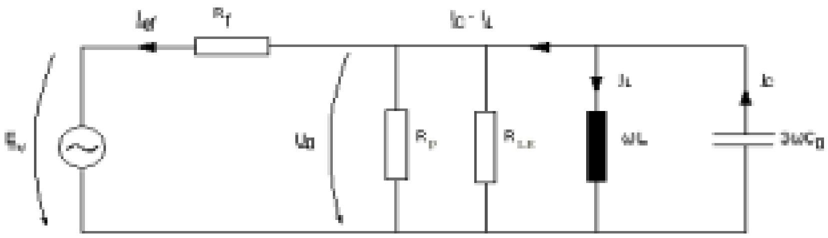

Fig. 6. Equivalent circuit for an earth fault in a network with a compensated neutral (Lehtonen & Hakola 1996).

Using the equivalent circuit of Fig. 6, we can write for the fault current:

$$I_{ef} = \frac{E\sqrt{1 + R_{LE}^2\left(3\omega C_0 - \frac{1}{\omega L}\right)^2}}{\sqrt{\left(R_f + R_{LE}\right)^2 + R_f^2 R_{LE}^2\left(3\omega C_0 - \frac{1}{\omega L}\right)^2}}. \tag{5}$$

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

$$I_{ef} = \frac{E}{R_{LE} + R_f} \tag{6}$$

The neutral voltage U_0 can be calculated correspondingly:

$$U_0 = \frac{I_{ef}}{\sqrt{\left(\frac{1}{R_{LE}}\right)^2 + \left(3\omega C_0 - \frac{1}{\omega L}\right)^2}} \tag{7}$$

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

$$\frac{U_0}{E} = \frac{R_{LE}}{R_{LE} + R_f} \tag{8}$$

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

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 indication for high resistance faults can be gained in the former case.

2.3 Networks with high resistance grounding

The grounding resistor may be connected in the neutral of a power transformer or across the broken delta secondary of three phase-to-ground connected distribution transformers. These systems are mainly used in MV and LV industrial networks where the continuity of service is important, because a single fault does not cause a system outage. If the grounding resistor is selected so that its current is higher than the system capacitive earth fault, then the potential transient overvoltages are limited to 2.5 times the normal crest phase voltage. The value of the grounding resistance is also limited by the thermal rating of the transformer winding.

Earth fault current can be calculated using the equivalent circuit of Fig. 7 as follows:

$$I_{ef} = \frac{E\sqrt{1+\left(R_e 3\omega C_0\right)^2}}{\sqrt{\left(R_f + R_e\right)^2 + \left(R_f R_e 3\omega C_0\right)^2}}. \qquad (9)$$

When the reactance of the earth capacitance is large compared to the earthing resistance, the above can be simplified as follows:

$$I_{ef} = \frac{E}{R_e + R_f} \qquad (10)$$

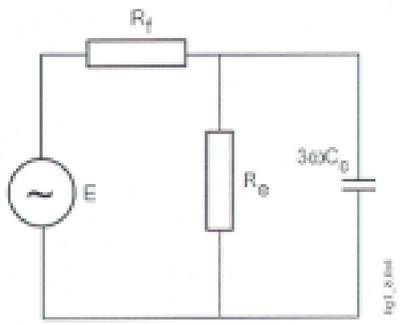

Figure 7. Equivalent circuit for the earth fault in a high-resistance earthed system (Lehtonen & Hakola 1996).

The neutral voltage is

$$U_0 = \frac{I_{ef}}{\sqrt{\left(\frac{1}{R_e}\right)^2 + (3\omega C_0)^2}} \tag{11}$$

The highest neutral voltage in high resistance earthed networks is equal to the phase to ground voltage when the fault resistance is zero. The corresponding phase to ground voltage in two sound phases is equal to the line voltage.

2.4 Sequence network representation

Symmetrical components are often used when analysing unsymmetrical faults in power systems. The various types of neutral earthing presented in sections 2.1- 2.3 can be analysed using the sequence network model and the appropriate connection of component networks, which depend on the fault type considered. The simplified equations in the previous sections can be derived from the general model.

For a phase to ground fault in radial operating system, the sequence networks and their interconnections are shown in Fig. 8. For example in unearthed network $\underline{Z}_e = \infty$ and the distributed capacitive reactances $\underline{X}_{1C}$, $\underline{X}_{2C}$ and $\underline{X}_{0C}$ are very large, while the series reactance (or impedance) values $\underline{Z}_{0l1}$, $\underline{Z}_{1l1}$, $\underline{Z}_{2l1}$, $\underline{Z}_{1T}$, $\underline{Z}_{2T}$, are relatively small. Thus, practically, $\underline{X}_{1C}$ is shorted out by $\underline{Z}_{1T}$ in the positive sequence network, and $\underline{X}_{2C}$ is shorted out by $\underline{Z}_{2T}$ in the negative sequence network. Since these impedances are very low, $\underline{Z}_{1T}$ and $\underline{Z}_{2T}$ approach zero relative to the large value of $\underline{X}_{0C}$. Therefore, the sequence currents can be approximated by the following equation in the case of zero fault resistance (Blackburn 1993).

$$\underline{I}_1 = \underline{I}_2 = \underline{I}_0 = \frac{\underline{E}_1}{\underline{Z}_{1T} + \underline{Z}_{1l1} + \underline{Z}_{2T} + \underline{Z}_{2l1} + \underline{X}_{0C}} \cong \frac{\underline{E}_1}{\underline{X}_{0C}} \tag{12}$$

and

$$\underline{I}_f = 3\underline{I}_0 = \frac{3\underline{E}_1}{\underline{X}_{0C}} \tag{13}$$

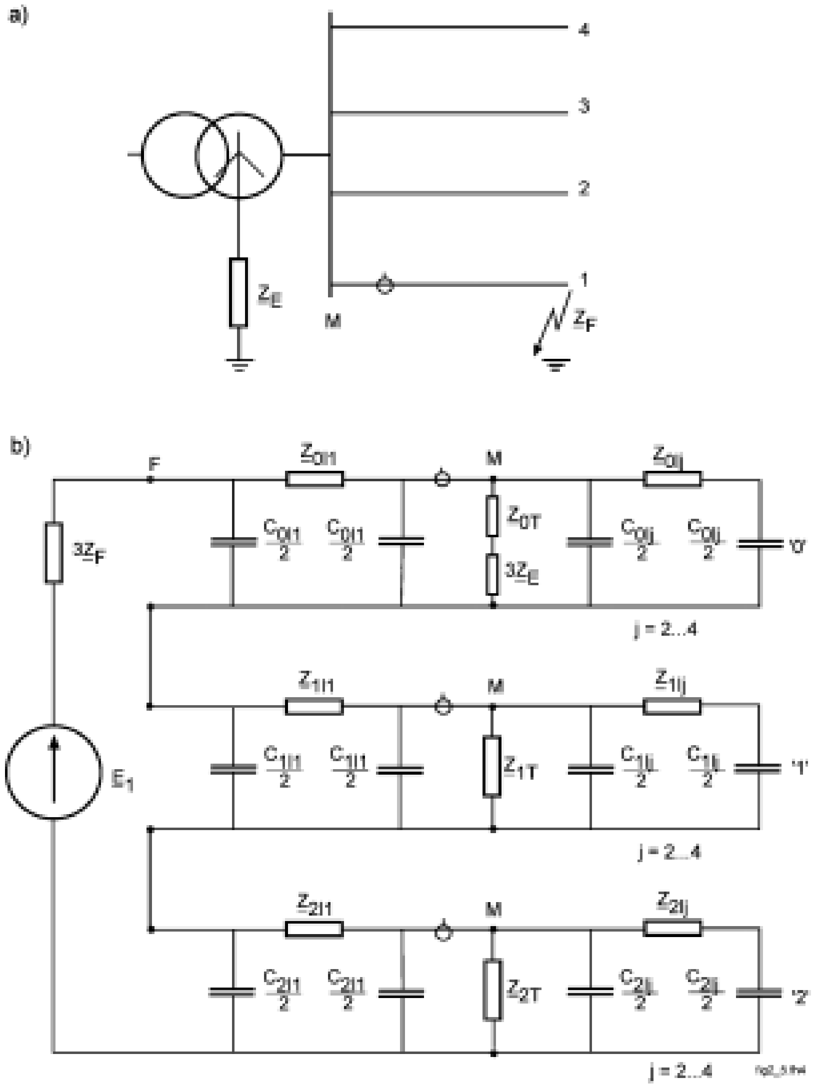

Figure 8. Single phase to earth fault in a distribution network. M is the measurement point, F refers to the fault location, $\underline{Z}_e$ is the earthing impedance and $\underline{Z}_f$ is the fault impedance. a) The network and b) the corresponding symmetrical component equivalent circuit. Z_{0T}, Z_{1T} and Z_{2T} are the zero sequence, positive sequence and negative sequence impedances of the substation transformer. j=2...4 refers to the impedances of the parallel sound lines (Lehtonen & Hakola 1996).

The unfaulted phase L2 and L3 currents will be zero when determined from the sequence currents of Eq. 12. This is correct for the fault itself. However, throughout the system the distributed capacitive reactances $\underline{X}_{1C}$ and $\underline{X}_{2C}$ are actually in parallel with the series impedances $\underline{Z}_{1l}$, $\underline{Z}_{1T}$ and $\underline{Z}_{2l}$, $\underline{Z}_{2T}$ so that in the system, $\underline{I}_1$ and $\underline{I}_2$ are not quite equal to $\underline{I}_0$. Thus the phase to ground capacitive currents $\underline{I}_{CE2}$ and $\underline{I}_{CE3}$ exist and are necessary as the return paths for the fault current $\underline{I}_f$. When faults occur in different parts of the ungrounded system, $\underline{X}_{0C}$ does not change significantly. Since the series impedances are quite small in comparison, the earth fault current is practically the same and is independent of the fault location. The zero sequence current measured at the substation comprises the current flowing in the fault point, less the portion that flows through the earth capacitances of the faulty line itself, see Fig. 8.

3. Review of the fault distance estimation methods

Methods based on the calculation of the faulty line impedance, on the fault generated travelling waves, and on Artificial Neural Networks (ANN) are very promising, when the fault distance is estimated using current and voltage measurements obtained from the substation in radial operated networks. In the travelling wave method, information about the fault position can be determined from the time difference between the incident travelling wave and its reflections. Bo et al. (1999) and Liang et al. (2000) have used transient voltage signals, and Xinzhou et al. (2000) have applied current travelling waves and wavelet transform. The main restrictions are the need for a very high sampling rate, in the range of MHz, and the difficulty in analysing the travelling waves and then extracting the fault information if the feeder has several branches (Abur & Magnago 2000).

Ground fault initial charge transients can be utilised for line impedance estimation. Schegner (1989) presented a very promising differential equation algorithm. The second proposed technique employed Fourier-transform methods, which solve the line impedance in the frequency domain. The reactance of the faulty line length is obtained directly as the imaginary part of the impedance calculated from the corresponding frequency spectrum components of the voltage and current (Igel 1990, Igel et al. 1991). Lehtonen (1992) developed a least-squares fitting method, which uses a modification of Prony's method for estimation of the transient parameters. The average error in field tests is reported to be a little more than 1 km when the fault resistance is 0 Ω, and the sampling rate is 10-20 kHz (Lehtonen 1995). Eickmeyer (1997), Eberl et al. (2000), and Hänninen & Lehtonen (2001) applied the neural network method trained by the transient samples of current and voltage signals. Hänninen et al. (1999) applied the wavelet method using field tests and real earth faults (Hänninen 2001). The accuracy achieved in the last mentioned cases was about 1 km in the field tests and 2 km for real earth faults. For the time being, the practical implementation of the transient based methods to numerical relays is restricted by the required sampling rate of 5 kHz. Winter (1993), Roman & Druml (1999) and Nikander (2002) have developed methods based on the use of fundamental frequency signals. The distance to an earth fault can be estimated with good sensitivity (high fault resistances) and accuracy in the special case of when it is possible to connect the faulty feeder to a closed ring with one healthy feeder.

In the following sections, three new algorithms are described for unearthed, compensated and resistance earthed networks. The aim of these methods is to enable online calculations in numerical relays. The main advantage of the algorithms is that they need only one measurement per primary transformer.

4. Supply bay measurement

The line length from substation to fault position can be estimated from current and voltage measurements in the supply bay in the case of a single-phase earth fault. The benefit of this method is that only one unit of measurement per primary transformer is needed, see Fig. 9. For the phase current and voltage measurement, the modern numerical relay, which is connected to the current and voltage transformers, can be utilised. Depending on the neutral point grounding, the state information of the circuit breaker on the faulty feeder or the state of the additional resistor across the suppression coil must be available. The faulty feeder and the starting time of the earth fault can be determined from the opening of the circuit breaker, by taking into account the delays in the protection relays.

The fault distance estimation algorithms use the fundamental frequency components of the current and voltage signals recorded during two network periods. For unearthed and resistance grounded networks, measurements taken at three different times are needed; i.e. pre-fault, fault and post-fault measurements. On the other hand, for compensated networks only two measurements are needed during an earth fault. The computation algorithm uses the phasor form for currents and voltages. The measuring algorithm runs continuously, and it saves the predetermined number of phasors for the distance computation.

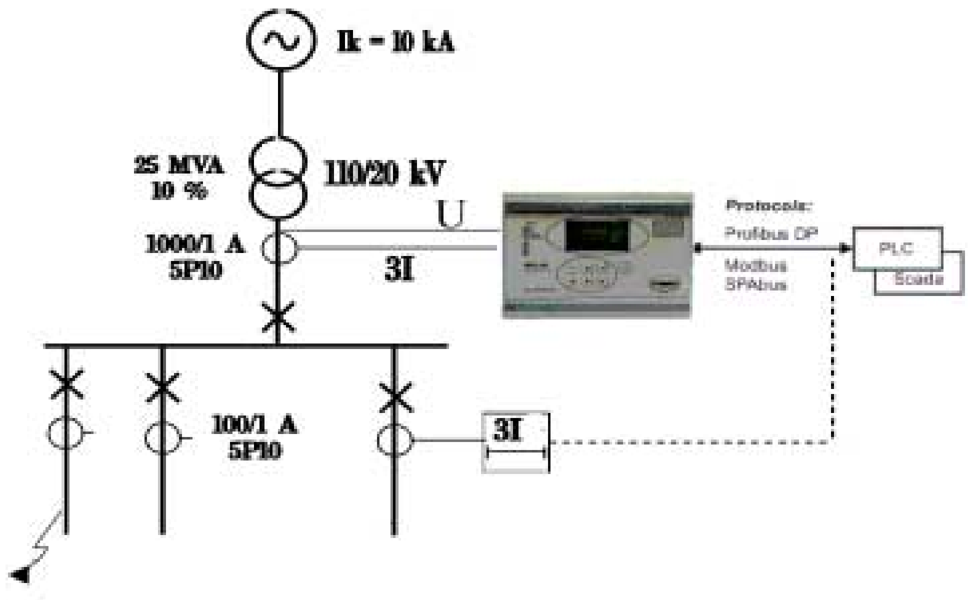

Figure 9. Schema of the supply bay measurements.

5. Fault distance computation in an unearthed network

The present application is intended for locating single-phase earth faults in an unearthed network. In order to quickly isolate and repair such a fault, the fault must be accurately located. Accurate fault location reduces the number of switching operations required to isolate a faulted line section after a permanent fault. This results in quick restoration of power supply to those customers not serviced by the faulted line section and further, facilitates quick repair of the faulted line section, thus speeding up the restoration of power to those customers serviced by the faulted line section.

When a fault occurs in a distribution network, existing relaying schemes typically make correct and fast tripping decisions based upon relatively simple measurements computed in real time. Such relaying schemes automatically isolate a faulted line section so that power distribution is maintained to unfaulted portions of the distribution network.

The fault location techniques are normally employed after the fault has occurred using stored fault data. The monitored data includes voltage and current waveform values at the line terminals before, during and after the fault. These values are either stored as waveform samples or computed phasors, by microprocessor based numerical relays installed at the power substation. In this novel application, the phase currents and voltages are measured in the supply bay, where the zero sequence current appears as zero due to the fact that the primary transformer at 20-kV substations normally has a Y/Δ-connection. Therefore, the fault current has to be evaluated based on the negative sequence component of the current.

The distribution feeders in distribution networks are normally arranged in a radial configuration with a number of tapped loads and several laterals. Typically, the voltage and current of a feeder are only measured at the substation from which the feeder originates, while the voltage and current of tapped loads and laterals are not measured. Thus, location of faults in distribution networks is substantially more complex than fault location on transmission lines, which do not have the increased complexity of tapped laterals having tapped loads.

Perhaps the most common type of fault location technique in distribution networks is the so-called “reactance method”. According to Fig. 10, the phase-to-earth voltage at the substation during an earth fault can be described by the following equation:

$$\underline{U}_L = p\underline{Z}_{L1}\underline{I}_{sf} + n\underline{Z}_{L1}\underline{I}_{sf}^{'} + R_f\,\underline{I}_f \qquad (14)$$

where $\underline{U}_L$ is the phase voltage;

$\underline{Z}_{L1}$ is the positive sequence line impedance;
R_f is the fault impedance;
$\underline{I}_{sf}$ is the phase current during the fault including the fault and load current;
$\underline{Z}_{tap}$ is the lumped impedance of the tap;
$\underline{I}_{tapf}$ is the current through the tap after the fault;
$\underline{I}'_{sf}$ is the current through the line after the tap and is equal to I_{sf}-I_{tapf};
p is the per unit distance between the source and the tap;
n is the per unit distance between the tap and the fault;
m is the per unit distance between the source and the fault and is equal p+n.

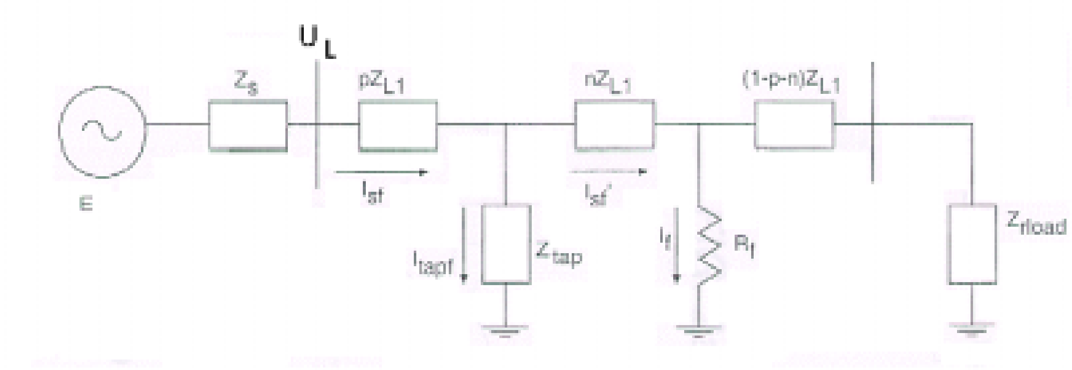

Figure 10. Simple schema of the network model used for fault distance calculation in the unearthed network (Novosel et al. 1998).

From equation 14, it is possible to derive an estimate for the fault distance. However, the problem with fault location is that the fault current $\underline{I}_f$, post-fault tap current $\underline{I}_{tapf}$, and fault resistance R_f are not accurately known. Many existing systems assume that the fault resistance is nearly zero. However, the value of the fault resistance may be particularly high for earth faults, which represent the majority of faults on overhead lines. Therefore, the combined effects of load current and fault resistance may substantially adversely affect simplistic calculations.

The reactance method compares the computed line reactance with the total line reactance or the real line reactance per kilometre, to determine the fault location. The fault location method described in this report attempts to improve upon the reactance method by making certain assumptions concerning the fault resistance and load current distribution along the feeder. Equation 14 can be presented in phasor form, where the phase current is subdivided into the load current and the fault current, and the tapped load is described by a load current distribution factor along the feeder.

$$\underline{U}_L = \frac{1}{3}s(\underline{Z}_0 + \underline{Z}_1 + \underline{Z}_2)\underline{I}_f + R_f\underline{I}_f + ks\underline{Z}_1\underline{I}_L \tag{15}$$

The relation of the load ($\underline{I}_L$) and fault ($\underline{I}_f$) current can be presented as follows:

$$\frac{\underline{I}_L}{\underline{I}_f} = \frac{I_L}{I_f}\cos\varphi_{Lf} + j\frac{I_L}{I_f}\sin\varphi_{Lf} \tag{16}$$

Substituting Eq. (16) into Eq. (15), the phase voltage can be determined;

$$\underline{U}_L = s\underline{I}_f\left\{\frac{1}{3}(R_0 + R_1 + R_2) + \frac{1}{3}j(X_0 + X_1 + X_2) + R_f\right\} + \tag{17}$$
$$s\underline{I}_f\left\{kR_1\frac{I_L}{I_f}\cos\varphi_{Lf} - kX_1\frac{I_L}{I_f}\sin\varphi_{Lf} + jkX_1\frac{I_L}{I_f}\cos\varphi_{Lf} + jkR_1\frac{I_L}{I_f}\sin\varphi_{Lf}\right\}$$

Using the reactance method and taking the imaginary part of the equation 17, the fault distance, s, can be solved as follows:

$$s = \left|\frac{\operatorname{Im}\left(\frac{\underline{U}_L}{\underline{I}_f}\right)}{\frac{1}{3}(X_0 + X_1 + X_2) + kX_1\frac{I_L}{I_f}\cos\varphi_{Lf} + kR_1\frac{I_L}{I_f}\sin\varphi_{Lf}}\right| \tag{18}$$

$X_{0,1,2}$ is the zero, positive and negative sequence reactance per kilometre of the line
R_1 is the positive sequence resistance per kilometre of the line
I_L is the absolute value of the load current
$\underline{I}_f$ is the absolute value of the fault current
φ_{Lf} is angle between the load and fault current phasors
k is the load current distribution factor
s is the estimated fault distance.

Three discrete measurements are needed. The notations used for the various current and voltage measurements are:

1) pre-fault measurement: $\underline{I}_{R1}$, $\underline{I}_{S1}$, $\underline{I}_{T1}$ & $\underline{U}_{R1}$, $\underline{U}_{S1}$, $\underline{U}_{T1}$

2) fault measurement: $\underline{I}_{R2}$, $\underline{I}_{S2}$, $\underline{I}_{T2}$ & $\underline{U}_{R2}$, $\underline{U}_{S2}$, $\underline{U}_{T2}$

3) post-fault measurement: $\underline{I}_{R3}$, $\underline{I}_{S3}$, $\underline{I}_{T3}$ & $\underline{U}_{R3}$, $\underline{U}_{S3}$, $\underline{U}_{T3}$

In the following, the algorithm for earth fault distance estimation is presented when the distribution network is unearthed and the phase currents and voltages are measured in the supply bay. The notations used in the algorithm apply to the case of a single phase earth fault in the R-phase. In addition to the measurements, the computation algorithm needs the zero, positive and negative sequence reactance per kilometre, and the positive sequence resistance per kilometre of the line as initial parameters.

<u>The computation algorithm</u>

1. The event that initiates the distance computation is the detection that a circuit breaker has opened. This also indicates the faulted feeder. This moment determines the time cycles for pre-fault, fault and post-fault measurements.

2. In the case of a low-impedance earth fault, the faulty phase is identified; e.g. from the fact that the absolute value of the voltage of the phase is decreased by half or more of its normal value, i.e. the following condition is valid:

$$|U_v| \leq 0.5|U_{vn}|, \tag{19}$$

   wherein $\underline{U}_v$ is the voltage of phase R, S, or T, and $\underline{U}_{vn}$ is the nominal value of phase voltage.

3. The reference for the measured quantities is determined. For the three discrete measurements, the corresponding phase-to-phase voltage of the two healthy phases is used.

4. In the case that fault occurs in the R-phase, the fault current is

$$\underline{I}_f = 3 * \Delta \underline{I}_2 \tag{20}$$

   where $\Delta\underline{I}_2$ is the change in the negative sequence component (measurement 2 minus measurement 1)

   If the faulty phase is S or T, the corresponding phase shift error (120° or 240°) must be taken into account.

5. The load current of the faulty feeder in phase R:

$$\underline{I}_L = (\underline{I}_{R1} - \underline{I}_{R3}) \frac{2\underline{U}_{R2} - \underline{U}_{S2} - \underline{U}_{S2}}{2\underline{U}_{R3} - \underline{U}_{S3} - \underline{U}_{S3}} \tag{21}$$

This equation compensates the effect that during the earth fault, the phase-to-phase voltage at the substation changes slightly, which causes a corresponding change in the load currents.

6. Computation of the fault distances with equation 18 using five different distribution factors for load current from k = 0.6 to k = 1.0, with a step of 0.1.

7. Comparison of the computed fault distances to the following distribution factor curve of the load current along the feeder

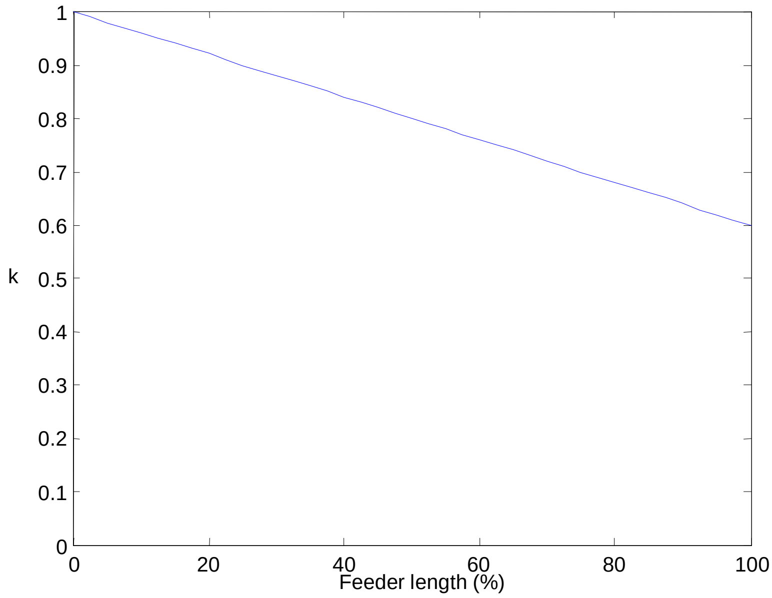

Figure 11. Distribution factor of the load current against feeder length presented in percentages

The fault distance is taken to be the one where the difference between the computed fault distance and the distance taken from Fig. 11 is the least. The comparison is made with 5 different distribution factor values of the load current. The result is acceptable provided that the difference divided by the faulted feeder length is smaller than 0.1.

The above mentioned algorithm was tested by simulating earth faults with the ATP-EMTP-program. The feeder length of the overhead network model was 370 km and the length of the faulted feeder was 40 km. Earth faults were simulated with fault resistance values of 10 Ω and 30 Ω with the faulted feeder both loaded and unloaded. The electrical loading of the healthy feeders was about 8 MVA and that of the faulted feeder about 2 MVA. On the faulted feeder, the loading was equally apportioned to four locations. The current and voltage measurements are presented in Fig. 9. The computed fault distances and errors are shown in Tables 1 and 2.

Table 1. Results of the earth fault distance computation in the unearthed network with no load on the faulted feeder. MEK is the mean absolute error in kilometres.

R_f =10 Ω Fault distance [km]	Computed distance [km]	Error [km]		R_f =30 Ω Fault distance [km]	Computed distance [km]	Error [km]
1	0,00	-1,00		1	0,00	-1,00
5	4,68	-0,32		5	4,68	-0,32
10	9,39	-0,61		10	9,39	-0,61
15	13,91	-1,09		15	13,99	-1,01
20	18,77	-1,23		20	18,79	-1,21
25	23,59	-1,41		25	23,60	-1,40
30	28,40	-1,60		30	28,49	-1,51
	MEK:	**1,04**			**MEK:**	**1,01**

Table 2. Results of the earth fault distance computation in the unearthed network with the faulted feeder loaded. MEK is the mean absolute error in kilometres.

R_f =10 Ω Fault distance [km]	Computed distance [km]	Error [km]		R_f =30 Ω Fault distance [km]	Computed distance [km]	Error [km]
1	0,00	-1,00		1	0,00	-1,00
5	5,22	0,22		5	5,09	0,09
10	10,36	0,36		10	10,09	0,09
15	16,16	1,16		15	15,66	0,66
20	25,10	5,10		20	24,48	4,48
25	25,01	0,01		25	24,17	-0,83
30	24,87	-5,13		30	23,75	-6,25
	MEK:	**1,86**			**MEK:**	**1,91**

The values in Tables 1 and 2 show that there is not a big difference in the result when the fault resistance is below 30 Ω. However, the loading of the faulted feeder affects the accuracy of the estimated distance. The mean absolute error in the distance estimation is about 1 km when the faulted feeder is unloaded, and about 2 km with heavy electrical loading. The benefit of the algorithm is that it is easy to implement into modern numerical relays. If better performance is needed, the factor k can be estimated by a network computation model for each candidate fault location.

6. Earth fault distance computation in the compensated network

In resonance grounded systems, the earth fault protection cannot be based on the reactive current measurement, since the current in 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 parallel resistor in the compensation equipment. The algorithm for earth fault location in the compensated network is simpler than the corresponding algorithm presented in the previous chapter. The main idea of the method is to measure changes in the zero sequence current and the faulty phase voltage when the additional resistance is switched parallel with the suppression coil during the fault, see Fig. 12. The change in the impedance of the zero sequence circuit induces corresponding changes in the zero sequence voltage and current. As an approximation, the change in the zero sequence voltage is considered to induce an equal change in the faulty phase voltage. In this case, the currents and voltages are also measured in the supply bay.

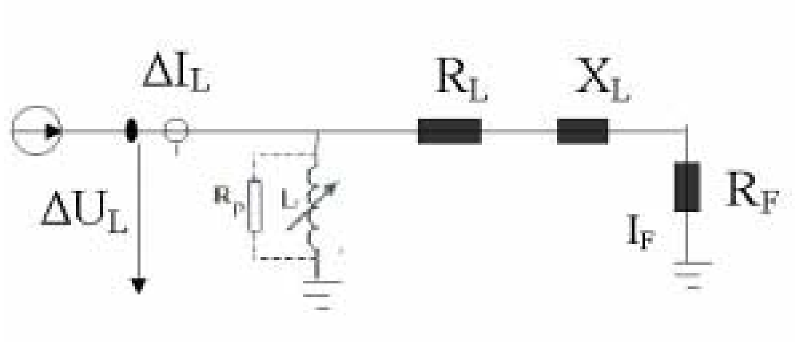

Figure 12. Simple schema of the network model used for fault distance calculation in the compensated network.

Two sequential measurements are needed. The notations for measuring currents and voltages are:

1) measurement during fault: $\underline{I}_{R1}$, $\underline{I}_{S1}$, $\underline{I}_{T1}$ & $\underline{U}_{R1}$, $\underline{U}_{S1}$, $\underline{U}_{T1}$

2) measurement after resistance switching: $\underline{I}_{R2}$, $\underline{I}_{S2}$, $\underline{I}_{T2}$ & $\underline{U}_{R2}$, $\underline{U}_{S2}$, $\underline{U}_{T2}$

In the following, the algorithm for earth fault distance estimation in the compensated network is presented when the phase currents and voltages are measured in the supply bay. The notation used in the algorithm corresponds to a single phase earth fault in the

R-phase. In addition to the measurements, the computation algorithm needs the zero, positive and negative sequence reactance per kilometre of the line as initial parameters.

The computation algorithm

1 The event that initiates the distance computation is detection of the switching on or off of the parallel resistor on the suppression coil. This moment determines the time cycles for the measurements. The faulted feeder can be determined from the opening of the circuit breaker.

2 In the case of a low-impedance earth fault, the faulty phase is identified; e.g. from the fact that the absolute value of the voltage of the phase is decreased by half or more of its normal value; i.e. the following condition is valid:

$$\left|U_v\right| \leq 0.5\left|U_{vn}\right|, \tag{22}$$

wherein $\underline{U}_v$ is the voltage of phase R, S, or T, and $\underline{U}_{vn}$ is the nominal value of the phase voltage.

3 The reference for the measured quantities is determined. For the two discrete measurements, the corresponding phase-to-phase voltage of the two healthy phases is used.

4 In the case that the fault occurs in the R-phase, the fault current change is

$$\underline{\Delta I}_f = 3 * \Delta\underline{I}_2 \tag{23}$$

where $\Delta\underline{I}_2$ is the change in the negative sequence component (measurement 2 minus measurement 1)

If the faulty phase is S or T, the relevant phase shift error (120° or 240°) must be taken into account.

5 The voltage change in the faulty phase

$$\Delta\underline{U}_R = \underline{U}_{R2} - \underline{U}_{R1} \tag{24}$$

6 The fault distance can be computed from the faulty line impedance:

$$\underline{Z} = \Delta\underline{U}_R / \Delta\underline{I}_f \tag{25}$$

By taking the imaginary part of the line impedance, the fault distance can be solved

$$s = \left| \frac{\mathrm{Im}(Z)}{\frac{1}{3}(X_0 + X_1 + X_2)} \right| \qquad (26)$$

where $X_{0,1,2}$ is the zero, positive and negative sequence reactance per kilometre of the line

The above mentioned algorithm was tested by simulating earth faults with the ATP-EMTP-program. The feeder length of the overhead network model was 370 km and the length of the faulted feeder was 40 km. Earth faults were simulated with fault resistance values of 10 Ω and 30 Ω when the faulted feeder was both loaded and unloaded. The electrical loading of the healthy feeders was about 8 MVA while the loading on the faulted feeder was about 2 MVA. On the faulted feeder, the loading was distributed evenly to four loading positions. The measurements of the currents and voltages are presented in Fig. 9. The computed fault distances and errors are in Tables 3 and 4.

Table 3. Results of the earth fault distance computation in the compensated network with the faulted feeder unloaded.

R_f =10 Ω Fault distance [km]	**Computed distance [km]**	**Error [km]**		**R_f =30 Ω Fault distance [km]**	**Computed distance [km]**	**Error [km]**
1	1,12	0,12		1	1,79	0,79
5	4,91	-0,09		5	5,52	0,52
10	10,36	0,36		10	10,97	0,97
15	14,96	0,04		15	15,67	0,67
20	20,65	0,65		20	21,31	1,31
25	25,20	0,20		25	26,00	1,00
30	30,65	0,65		30	31,51	1,51
	MEK:	**0,30**			**MEK:**	**0,97**

Table 4. Results of the earth fault distance computation in the compensated network, with the faulted feeder loaded.

R_f =10 Ω Fault distance [km]	Computed distance [km]	Error [km]		R_f =30 Ω Fault distance [km]	Computed distance [km]	Error [km]
1	1,22	0,22		1	2,05	1,05
5	5,11	0,11		5	6,04	1,04
10	10,94	0,94		10	12,00	2,00
15	15,73	0,73		15	17,05	2,05
20	21,83	1,83		20	23,17	3,17
25	26,81	1,81		25	28,35	3,35
30	32,85	2,85		30	34,48	4,48
	MEK:	**1,21**			**MEK:**	**2,45**

The results presented in Tables 3 and 4 show that there is not a big difference in the result when the fault resistance is below 30 **Ω**. This is due to the fact that the fault resistance is small compared to the additional resistor connected in parallel with the suppression coil. However, the loading of the faulted feeder affects the accuracy of the estimated distance. The mean absolute error in the distance estimation is about 1 km when the faulted feeder is unloaded and about 2,5 km with heavy electrical loading.

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7. Earth fault distance computation in the resistance grounded network

In Finland, medium voltage distribution networks are unearthed (80 %) or compensated (20 %) (Nikander & Lakervi 1997). However, in other countries it is usual for networks to use different types of impedance earthing. Impedance earthing involves connecting a low resistance between the system neutral point and earth, see Fig. 13. For the export industry of the Finnish relay manufacturer, a method is developed for fault distance estimation in resistance grounded systems.

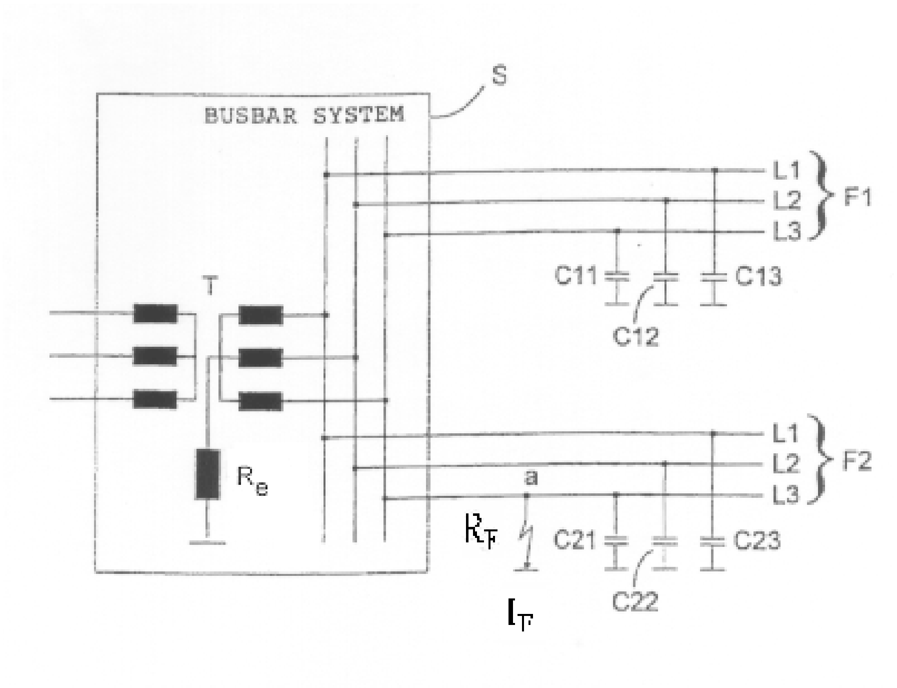

Figure 13. *Simple schema of the network model used for fault distance calculation in the resistance earthed network.*

In resistance earthed systems, it is also possible to estimate the fault distance based on measurements made in the supply bay. The developed algorithm can easily be modified for cases where the voltages and currents are measured at the beginning of the outgoing feeders. The following three discrete measurements are needed:

1) pre-fault measurement: $\underline{I}_{R1}$, $\underline{I}_{S1}$, $\underline{I}_{T1}$ & $\underline{U}_{R1}$, $\underline{U}_{S1}$, $\underline{U}_{T1}$

2) fault measurement: $\underline{I}_{R2}$, $\underline{I}_{S2}$, $\underline{I}_{T2}$ & $\underline{U}_{R2}$, $\underline{U}_{S2}$, $\underline{U}_{T2}$

3) post-fault measurement: $\underline{I}_{R3}$, $\underline{I}_{S3}$, $\underline{I}_{T3}$ & $\underline{U}_{R3}$, $\underline{U}_{S3}$, $\underline{U}_{T3}$

A similar algorithm to that used for the unearthed system can be applied for fault distance estimation with small modifications to the system, which is earthed with a small resistor. The notations used in the algorithm apply to the case of a single phase earth fault in the R-phase. In addition to the measurements, the computation algorithm needs the zero, positive and negative sequence reactance per kilometre, and the positive sequence resistance per kilometre of the line, as initial parameters.

The computation algorithm

1) The event that initiates the distance computation is detection that a circuit breaker has opened. This also indicates the faulted feeder. This moment determines the time cycles for pre-fault, fault and post-fault measurements.

2) In the case of a low-impedance earth fault, the faulty phase is identified; e.g. from the fact that the absolute value of the voltage of the phase has decreased to less than half of its normal value, i.e. the following condition is valid:

$$\left|\underline{U}_v\right| \leq 0.5\left|\underline{U}_{vn}\right|, \tag{27}$$

wherein $\underline{U}_v$ is the voltage of phase R, S, or T, and $\underline{U}_{vn}$ is the nominal value of the phase voltage.

3) The reference for the measured quantities is determined. For the three discrete measurements, the corresponding phase-to-phase voltage of the two healthy phases is used.

4) In the case that the fault occurs in the R-phase, the fault current is

$$\underline{I}_f = 3 * \Delta\underline{I}_2 \tag{28}$$

where $\Delta\underline{I}_2$ is the change in the negative sequence component (measurement 2 minus measurement 1)

If the faulty phase is S or T, the appropriate phase shift error (120° or 240°) must be taken into account.

The alternative possibility is to approximate the fault current based on the zero-sequence current, if the primary transformer connection is Yy at the substation:

$$\underline{I}_f = 3\Delta\underline{I}_0 = \left(\underline{I}_{R2} + \underline{I}_{S2} + \underline{I}_{T2}\right) - \left(\underline{I}_{R1} + \underline{I}_{S1} + \underline{I}_{T1}\right) \tag{29}$$

5) The load current $\underline{I}_L$ of the faulty feeder in phase R is derived by taking into account the phase-to-phase voltage drop caused by the earth fault:

$$\underline{I}_L = \left(\frac{\underline{I}_{11} - \underline{I}_{13}}{\underline{I}_{11}} \right) \underline{I}_{R1} \frac{2\underline{U}_{R2} - \underline{U}_{S2} - \underline{U}_{S2}}{2\underline{U}_{R1} - \underline{U}_{S1} - \underline{U}_{S1}} \tag{30}$$

where $\underline{I}_{11}$ is the positive sequence component of the pre-fault current and $\underline{I}_{13}$ is the positive sequence component of the post-fault current.

6) The fault distance can be solved from the following equations. For example, in the case of a low resistance single phase earth fault in phase R:

$$\underline{U}_{R2} = \underline{Z}_L \underline{I}_f + k \underline{Z}_1 \underline{I}_L \tag{31}$$

$\underline{Z}_L$ is the line impedance
$\underline{Z}_1$ is the positive sequence line impedance
k is the load current distribution factor.

By taking the imaginary part, the line reactance can be solved:

$$X = \operatorname{Im}(\underline{Z}_L) = \operatorname{Im}\left(\underline{U}_{R2} \Big/ \left(\underline{I}_f + k \underline{I}_L \, {}^{Z_1}\!/_{Z_L} \right) \right) \tag{32}$$

Z_1/Z_L is the absolute value relation of the positive sequence line impedance to the line impedance

The estimated fault distance s is:

$$s = \left| \operatorname{Im}(\underline{Z}_L) \Big/ \tfrac{1}{3}(X_0 + X_1 + X_2) \right| \tag{33}$$

The aforementioned algorithm can be implemented in a modern numerical relay. As a result, the algorithm gives the line reactance value from the substation to the fault position. Alternatively, the relay can give the estimated fault distance if the sequence line reactances per kilometre are stored as initial parameters in the relay. The line sequence reactance values can be obtained from the catalogues or determined by measuring. For the load current distribution factor *k*, a suitable initial value is between 0,5-0,6, which means that the electrical loading is evenly distributed on the feeder.

The algorithm detailed above was tested by simulating earth faults with the ATP-EMTP-program. The feeder length of the overhead network model was 370 km and the length of the faulted feeder was 40 km. Earth faults were simulated with a fault resistance value of 1 Ω in one kilometre steps, with the loading of the faulted feeder at about 2 MVA. On the faulted feeder, the loading was distributed evenly to four loading positions. The currents and voltages were measured as presented in Fig. 9. The earthing resistor was set to 20 Ω, giving rise to fault currents ranging from 300 A to 700 A depending on the fault distance. The computed fault distances and errors are listed in Table 5. The whole electrical loading was 10,4 MVA measured in the supply bay. In Table 5, U_{R2} is the phase voltage during the fault, I_L is the load current of the faulted feeder, I_f is the fault current.

The results with a small fault resistance and heavy electrical loading are more accurate compared to the results in unearthed or compensated systems. This is because the fault current is normally higher when the system is earthed with a small resistor. The mean error in kilometres is about 0,5 km.

Table 5. Errors in fault distance estimation computed with two load current distribution factors in a resistance earthed network. Fault resistance is 1 Ω.

Real distance [km]	**U_{R2}/[V]**	**I_L/[A]**	**I_f/[A]**	**k1=0,5 Error/ [km]**	**k2=0,625 Error/ [km]**
1	1295,59	138,07	764,39	-0,07	-0,05
2	1891,60	137,54	744,91	-0,08	-0,11
3	2485,64	137,00	725,66	-0,10	-0,16
4	3061,36	136,47	706,73	-0,13	-0,20
5	3611,98	135,95	688,19	-0,14	-0,24
6	4141,47	135,43	670,07	-0,15	-0,27
7	4638,81	134,91	652,41	-0,17	-0,31
8	5113,97	134,40	635,23	-0,17	-0,33
9	5566,53	133,89	618,56	-0,17	-0,35
10	5991,99	133,39	602,40	-0,17	-0,38
11	6397,57	132,89	586,75	-0,16	-0,39
12	6781,40	132,39	571,61	-0,15	-0,41
13	7146,16	131,90	556,98	-0,13	-0,41
14	7492,59	131,41	542,85	-0,11	-0,42
15	7820,02	130,93	529,21	-0,09	-0,42
16	8127,42	130,45	516,04	-0,06	-0,42
17	8426,05	129,97	503,33	-0,02	-0,41
18	8706,63	129,50	491,08	0,02	-0,41
19	8972,06	129,03	479,26	0,06	-0,39
20	9227,68	128,56	467,86	0,11	-0,37
21	9468,23	128,10	456,85	0,16	-0,36
22	9702,24	127,64	446,25	0,22	-0,33
23	9919,65	127,18	436,00	0,24	-0,30
24	10129,28	126,73	426,12	0,35	-0,26
25	10328,41	126,28	416,59	0,42	-0,23
26	10520,86	125,83	407,38	0,51	-0,18
27	10701,58	125,39	398,49	0,58	-0,14
28	10875,83	124,95	389,90	0,67	-0,09
29	11044,90	124,52	381,60	0,76	-0,04
30	11201,84	124,08	373,58	0,86	0,05
31	11353,58	123,65	365,82	0,95	0,07
32	11501,38	123,23	358,32	1,07	0,14
33	11641,93	122,80	351,07	1,18	0,21
34	11777,57	122,38	344,04	1,30	0,29
35	11907,02	121,97	337,25	1,42	0,37
36	12031,08	121,55	330,66	1,55	0,45
37	12150,46	121,14	324,28	1,68	0,53
38	12264,77	120,73	318,10	1,81	0,62
39	12374,16	120,33	312,10	1,95	0,71
40	12482,45	119,93	306,29	2,10	0,82
			MEK	**0,55**	**0,32**

8. Conclucions

This report describes three novel methods for earth fault location in unearthed, compensated and low-resistance earthed networks. 20 kV medium voltage distribution networks are either unearthed or compensated in Finland. Therefore, the algorithm for low-resistance earthed networks is primarily intended for the export industry of the Finnish relay manufacturers. The developed algorithms are based on the use of fundamental frequency signals, and they need only one measurement unit per primary transformer at the substation. The fault current can be determined from the negative sequence component of the measured signal in the supply bay. The scope is restricted to radially operated systems with a number of tapped loads and several laterals.

In the case of unearthed and resistance grounded networks, three different measurements, spaced in time, are needed for fault location purposes and these are: pre-fault, fault and post-fault measurements. The computation algorithms need the zero, positive and negative sequence reactance, and the positive sequence resistance per kilometre of the line as initial parameters. Due to tapped loads, the load current distribution factor has to be available or it must be estimated.

In a compensated network, however, only two measurements are required during an earth fault. The main idea behind the method is to measure the changes in the zero sequence current and the faulty phase voltage when the additional resistance, which is in parallel with the suppression coil, is switched on or off during the fault. The computation algorithm needs the zero, positive and negative sequence reactance per kilometre of the line as initial parameters.

The soundness of the algorithms was tested using simulated data. According to the results, the performance of the methods is good enough for practical use, and most likely the accuracy will be comparable to the transient based methods. The algorithms were tested with the faulty feeder both loaded and unloaded with 10 – 30 Ω fault resistances. The error in distance computation was about 1 - 2 km, depending on the loading and the fault resistance value.

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Title
Earth fault distance computation with fundamental frequency signals based on measurements in substation supply bay

Abstract

This report describes three novel methods for earth fault location in unearthed, compensated and low-resistance grounded networks. The 20 kV medium voltage distribution networks are either unearthed or compensated in Finland. The last mentioned algorithm is therefore primarily intended for the export industry of the Finnish relay manufacturers. The developed algorithms are based on the use of fundamental frequency signals, and they need only one measurement unit per primary transformer at the substation. This is due to the fact that the fault current can be determined from the negative sequence component of the measured signal in the supply bay. The scope is restricted to radially operated systems. The earth fault distance location is based on the line impedance calculation in these algorithms.

For unearthed and resistance grounded networks, measurements at three discrete times are needed for fault location purposes; pre-fault, fault and post-fault measurements. In the compensated network though, only two measurements, taken during the earth fault, are needed.

The soundness of the algorithms was tested using simulated data. According to the results, the performance of the methods is good enough for practical use, and most likely the accuracy is comparable to the transient based methods. The algorithms were tested when the faulty feeder was both loaded and unloaded, with 10 – 30 Ω fault resistances. The error in distance computation was about 1- 2 km, depending on the loading and the fault resistance value.

Keywords
power systems, power distribution networks, electrical faults, earth fault, positioning, fault resistance, distance, calculation, algorithms, signal processing

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