Earth Faults in Extensive Cable Networks

Electric Distribution Systems

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Licentiate Thesis
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Abstract

The amount of underground cable in the Swedish rural distribution systems has increased considerably since the 2005 Gudrun hurricane. The resulting new rural networks combine the long line sections of the traditional rural networks that they replace, with the use of cable, common in urban networks. The introduction of long cables is a technology change and as such, it influences the distribution system earth fault behaviour. This work explains why the earth fault behaviour of electric distribution systems with long cables is different from that of conventional systems consisting of short cable feeders. The analysis in this work is carried out by use of circuit theory. The obtained results are compared to and found in accordance with time simulations.

In terms of equivalent impedance and earth fault behaviour, the main difference between the new rural cable distribution systems and conventional urban systems, is that the zero sequence series impedance of the rural systems is not necessarily negligible. Since the zero sequence series impedance is partly resistive, the equivalent impedance of the system has a resistive component that cannot be compensated for by use of conventional resonance earthing. The zero sequence resistance damps the resonance of the system and by that influences the earth fault behaviour. The damping might result in large low-impedance fault currents and difficulties to detect high-impedance faults. The influence of the zero sequence series impedance on the equivalent impedance and the earth fault behaviour depends on the fault location.

The zero sequence series parameters of cables are much different from those of overhead lines. Consequently, fundamental frequency and harmonic resonance is reached for considerable shorter cables than overhead lines. In addition, feeders that combine overhead lines and underground cables might give rise to series resonance. The zero sequence parameters of underground cables, and by that the earth fault behaviour, depend on the cables properties as well as the cable installation. One important finding of this work is that the zero sequence impedance is not necessarily proportional to the cable length.

Distributed compensation increases the shunt impedance of underground cables so that the influence of the series impedance decreases. If the local compensation coils are accurately dimensioned, the series impedance is negligible and does not contribute to the equivalent system resistance and the resonance damping. There are resistive losses in the local Petersen coil, which to some extent damp the resonance. The equivalent zero sequence resistance is however considerable smaller than that of systems with central compensation. Distributed compensation can thus be considered as an efficient way to make the earth fault behaviour of systems with long cables similar to that of traditional systems with short cables.

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Lund, December 2008
Anna Guldbrand

Contents

Chapter 1

Introduction

Our present lifestyle depends on reliable access to electrical energy. To provide the energy, we need power plants for generation and power networks for transmission and distribution. The generation, transmission and distribution systems are continuously developed to improve the reliability of energy supply and the system efficiency. The development sometimes leads to new technologies that are introduced in the systems. The introduction of new technology can however have different and wider spread consequences to the system than those originally intended. This licentiate thesis concerns development and technology changes in distribution systems.

1.1 Motivation of the study

Swedish continuity of supply was brought to the fore in January 2005 when hurricane Gudrun swept the country. 75 million m^3 of wood were brought down causing severe damage to electric distribution networks. The power failures affected more than 730 000 consumers, some lacking power for several weeks (Palm 2008). Neither network owners nor government officials are able to prevent storms like Gudrun but must instead provide against damages and power outages caused by the storms.

One way to provide against power outages is to use electrical distribution networks that can withstand bad weather conditions. Figure 1.1 shows outage data from the Gudrun hurricane. The data show that consumers connected to rural distribution systems consisting of overhead lines in general experienced more outages compared to consumers connected to cable systems (ER 16:2005). The Gudrun experience thereby confirmed what long time operation statistics show; cables withstand bad weather conditions better than overhead lines.

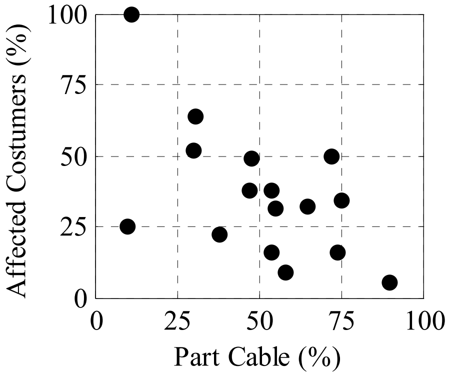

Figure 1.1 Relation between outage rate during hurricane Gudrun and part cable in distribution systems (for distribution network companies in the area).

At the time of the Gudrun hurricane, the Swedish rural distribution networks were mainly consisting of overhead lines. Network operators became heavily criticised for neglecting continuity of supply and rural consumers. Although an industry-initiated program to increase distribution system reliability was already in progress, the Swedish parliament found it necessary to strengthen the rights of network consumers by regulating consumer power outage compensation in the electricity act (1997:857). Costs associated to consumer compensation and a growing concern about name and reputation, have increased the distribution network owner incentive to secure continuity of supply. It has accelerated the process of replacing rural overhead lines with underground cables.

The amount of underground cable in Swedish rural distribution systems has increased considerably since the 2005 hurricane and further overhead line to cable replacements are expected (E.ON 2008). The resulting new rural networks will combine the long line sections of the traditional rural network that they replace, with the use of cable, common in urban networks. The systems therefore differ from traditional rural systems consisting of long overhead lines as well as from traditional urban systems consisting of several relatively short cables.

The introduction of long cables is a technology change and as such, it raises several questions: Will the system behaviour be affected? What part of the system analysis will be affected? Why is the system behaviour affected? What system behaviour is to expect?

To answer the above questions, re-evaluation of distribution system analysis and operation is necessary, taking distribution systems with long cables into consideration.

The most important aspect of power system design is safety. The power system shall be constructed in such way that not even during a fault shall anyone be exposed to danger. The most common type of fault in the electrical distribution system is earth faults (Hänninen et al. 2001). During an earth fault, a current flows from the electric network to earth, at the fault location. Apart from being a danger as such, the current can energise different parts of the power system and the surrounding area.

The earth fault currents and the voltage rise is normally analysed as part of the network planning procedure. This is typically done using a standard procedure that is based on a number of assumptions. A key assumption is that the total cable length but neither the structure of the network nor the fault location influence the earth fault behaviour of the system. The introduction of long underground cables motivates reconsideration of the above assumptions. The influence of network structure and fault location on the earth fault behaviour in systems with long cables is therefore studied in this work.

A new, distributed earthing method has been introduced in Swedish electrical distribution networks. Within this work, the earth fault behaviour in long cable systems with distributed compensation will be compared to the earth fault behaviour in systems with conventional central system earthing. The comparison will focus on the influence of distributed compensation on earth fault currents and voltage rise. The work concerns medium voltage networks, typical with system voltage 10 or 20 kV.

1.2 Objectives

There are two main objectives of this thesis. The first is to investigate the earth fault behaviour of electric distributions systems consisting of long cable feeders. The earth fault behaviour of these systems shall be compared to that of conventional systems consisting of shorter cables, so that possible differences are identified. The earth fault behaviour of systems with long feeders only consisting of cable, as well as feeders that are combinations of overhead line and cable shall be studied.

The second main objective is to investigate the influence of the system earthing on long cable feeder systems. The influence of distributed compensation shall be compared to that of traditional system earthing.

The earth fault behaviour includes a variety of characteristic and quantities. In this thesis, the focus shall be on maximum earth fault current and neutral point displacement voltage and high-impedance fault detection. The maximum earth fault current is a worst-case scenario in terms of power system safety. It is also central to the possibility of arc fault self-extinction in systems consisting exclusively or partly of overhead lines. Earth fault detection is a requirement for fault localisation, disconnection and restoration.

The analysis is based on the electric properties of the cables. These properties vary depending on the dimensions and installation of the cable. This work shall therefore include a study of how the earth fault behaviour responds to changes in the electric properties of the cables.

1.3 Outline of the Thesis

Chapter 2 starts with an introduction of the risks associated to human current exposure, and a brief explanation of the measurement that are taken to prevent severe accidents.

In Chapter 3, symmetrical components and sequence representation of earth faults are introduced. Chapter 3 also treats differences between electric parameters of overhead lines and cables.

Chapter 4 is an overview of conventional methods of system earthing. Isolated neutral systems, resistance earthed systems and resonance earthed systems are described by use of phase components as well as symmetrical components. In addition, Chapter 4 introduces resonance earthing by use of distributed compensation.

In Chapter 5, long cables are introduced. Conventional earth fault analysis assumptions are assessed for use on systems with long cable feeders.

In Chapter 6, circuit analysis is used to study the influence of the network structure and fault location on the earth fault behaviour. Series resonance in long cable feeders is also treated.

Chapter 7 treats distributed compensation. The influence of local coils on the earth fault behaviour is explained. In addition, series resonance in feeders that consist of overhead lines as well as underground cable and the influence of zero sequence impedance on the earth fault behaviour is studied.

Chapter 8 presents how cable dimensions and installation parameters influence the zero sequence series impedance of underground cable.

In Chapter 9, time simulations are used to assess the results of the circuit analysis and to study the influence of transformer impedance.

The outcome of this thesis is discussed in Chapter 10. Suggestions of further work related to the licentiate thesis are also included in this chapter.

Reading advice

The first four chapters can be read as an introduction to the subject and to conventional earth fault analysis. Some understanding of symmetrical components is helpful to understand the analysis carried out from Chapter 3 and forward.

Readers who already have general knowledge about conventional electrical distribution systems may want to start there reading with Chapter 5, in which long cable feeders are first introduced.

1.4 Contributions

The main contribution of this work is to explain why the earth fault behaviour of electric distribution systems consisting of long cables is different from that of conventional systems consisting of short cable feeders. The work does also show that results obtained from circuit analysis are in accordance with results obtained from time simulations.

The work explains why the zero sequence series impedance reaches non-negligible values in very long strictly radial cable feeders as well as branched cable feeders. It also explains how the resistive part of the equivalent zero sequence impedance of long cables damp the resonance of conventionally resonance earthed systems, and how this results in large low-impedance fault currents and possible difficulties to detect high-impedance faults.

The work shows that since the zero sequence parameters of cables are much different from those of overhead lines, fundamental frequency resonance is reach for considerable shorter transmission lines.

In this work, it is explained why the low-impedance earth fault behaviour of long cable systems depends on the location of the fault, and why the zero sequence voltage is not equal all over the systems.

The work describes how the zero sequence parameters of underground cables depend on cables properties and installation. One important finding of this work is that the zero sequence impedance is not necessarily proportional to the cable length.

It is explained why feeders that are combination of overhead lines and cables might lead to series resonance and high resistive earth fault currents.

Finally, the work describes how distributed compensation increases the shunt impedance of underground cables and that the impact of the series impedance thereby is negligible and the equivalent zero series resistance of the system considerable decreased.

Chapter 2

Earth faults and personal safety

The three most important aspects of distribution system design are safety, reliability and economy. The safety is of highest priority, followed by reliability and economy. Power system safety mainly concerns current exposure. Current exposure can cause serious harm to the human body and even prove fatal. The consequences of current exposure depend on current amplitude as well as current duration. To ensure safety, the power systems include protection that limits the duration of faults.

This work focuses entirely on earth faults. Requirements on earth fault current amplitude as well as earth fault current duration in the Swedish power system are issued as government regulations (ELSÄK-FS 2008:1).

2.1 Effects of current on humans

A voltage applied across the human body will create a current. The current is limited by the magnitude of the voltage and the body impedance:

$$I_{body} = \frac{U_{body}}{Z_{body}} \tag{2.1}$$

The body impedance shows a non-linear relation to the applied voltage. It is considered mostly resistive and it varies depending on several different factors, among these are humidity and body mass. According to IEC standards (IEC 2005), the approximate body resistance is between 575 (5 % of the population) and 1050 Ω (95 % of the population) assuming large contact areas and an applied voltage that exceeds 1000 V. An applied voltage of 100 V will result in a body resistance between 990 (5 %) and 3125 ohm (95 %).

The consequence of electricity exposure to the human body is limited by the amplitude and duration of the current, but the voltage level is relevant as it, in combination with the body impedance, determine the current. The effects of current exposure range from perception and loss of muscular control to respiratory problems, ventricular fibrillation and cardiac standstill (Bernstein 1991):

- The current threshold for *perception* is less than 1 mA (IEC 2005) (Lindahl et al. 1990). A 1 mA current is not dangerous as such but the sensation might give people unintentional reactions with possibly dangerous consequences, such as falls.

- If, what is called, the let go current level is exceeded the exposed person *cannot control the muscles* to let go of energized equipment. This current level is in the range of 5 to 10 mA (IEC 2005). It is painful and if the situation continues long enough the body resistance might decrease, current level increase and the consequences become severe and even lethal.

- *Respiratory problems* normally occur in the range of 20 to 40 mA, depending on current duration. If the exposure remains for several seconds, the risk of remaining injuries is large.

- *Ventricular fibrillation* is a life threatening condition that can only be stopped by the use of defibrillation. The threshold for ventricular fibrillation depends on current duration T and is estimated according to (Bernstein 1991):

  $$\begin{gathered} I = \frac{100}{T} mA \\ 0.2s \le T \le 2s \end{gathered} \tag{2.2}$$

  500 mA is considered the ventricular fibrillation threshold for current exposure shorter than 0.2 s and 50 mA is considered the ventricular fibrillation threshold if the current exposure exceeds 2 s. The probability of ventricular fibrillation depends on the phase of the current and where in the cardiac circle the body is exposed to the current.

2.2 Personal safety during earth faults

A power system earth fault is an electrical connection between at least one phase and earth. This connection constitutes a potential threat to the safety of nearby humans and livestock, and to the power system equipment. The connection between the phase and earth might be formed by a human body. If this is the case, the main part of the pre fault phase to earth voltage is applied across the body and the current that flow through it is large. These accidents are severe but rare. Most earth faults start from other reasons than phase-human-earth connection, but since the faults energize power system equipment, they can still affect people that are close to or in contact with the equipment.

Energizing of electrical equipment

The earth fault current path is associated to certain impedance. This impedance is mainly resistive and therefore referred to as the resistance to earth. The impedance gives rise to a voltage that might energize electrical equipment in the power system and the surrounding area. Large fault current and current path impedance will result in a large voltage rise and hence be a threat to personal safety. The power system design shall ensure that the voltage level is kept low wherever any humans or livestock can be expected to touch or step. The maximum tolerable voltage level of electrical equipment in the Swedish power systems is regulated by the regulations (ELSÄK-FS 2008:1).

The Swedish regulations consider the results of the IEC technical specification 60479-1 (IEC 2005). The IEC 60479-1 specifies how electric currents affect the human body and state thresholds for tolerable body current. The current thresholds have been used to calculate tolerable step and touch voltages and these voltage values have been adopted in the Swedish regulations. According to the regulations, the voltage of protective earth conductors, possibly combined with neutral (PEN), may not exceed 100 V (200 V with separate LV earthing). In practice, this means that the voltage across the resistance to earth may not exceed 100 V during an earth fault in high voltage installations which nominal voltage does not exceed 25 kV (ELSÄK-FS 2008:1).

Earth fault current and earthing resistance

It is the resulting resistance to earth (current path impedance) and the total earth fault current that determine the potential rise of electrical equipment and surrounding area. The resulting earthing resistance includes all galvanic connected connections to earth, including cable shields and additional copper wires. Each new underground cable forms an additional connection to earth and is thereby likely to decrease the resulting earthing resistance. The total earth fault current includes the currents in all conductors that make up the resulting earthing resistance.

The exact value of the resulting resistance to earth is often unknown. Instead, the earthing is considered acceptable if it prevents the voltage across the earthing resistance to exceed regulatory limits. The maximum tolerable earth fault current is thereby limited by maximum tolerable voltage and the resulting earthing resistance:

$$I_{max} = \frac{U_{max}}{R_{earth}} \tag{2.3}$$

In order to find the maximum tolerable current and thereby be able to interpret the results of the earth fault analysis performed in this work, it is necessary to find an approximate value of typical rural distribution earth fault resistances.

The earth fault current in traditional Swedish rural distribution networks is typically in the order of 10 to 15 A. The earthing of these systems has been designed to limit the voltage rise to 100 V. It is therefore reasonable to assume that the size of the resulting earth fault resistance in these systems is kept below 7 or 8 Ω. As mentioned above, an increased amount of cable is likely to decrease the earthing resistance and a total fault current of approximately 20 A might therefore be considered tolerable in systems with an extensive use of cable.

High-impedance earth fault detection

One part of the Swedish regulations (ELSÄK-FS 2008:1) addresses high-impedance fault detection. Typical high-impedance faults in overhead line systems are broken conductor that falls to the ground or on to other conducting materials (Aucoin 1996). If these faults are left unattended, the broken conductors will remain energized on the ground and thereby be a potential danger to the public. High-impedance earth faults in cable systems are generally not as much of a potential danger to personal safety as the overhead line faults. This is because most broken underground cables are not in reach of the public. This difference is reflected in the regulations. The regulations require that all earth faults with fault impedance below 3 kΩ (5 kΩ if covered conductor) are detected and disconnected in systems that consist partly or entirely of overhead lines. In systems without any overhead lines, the requirements are limited to detection only (ELSÄK-FS 2008:1).

Arcing faults self extinction

Although it is important to detect and disconnect permanent earth faults, many overhead line earth faults are temporary arcing faults that do not have to be disconnected. If these faults are cleared by self-extinction, the distribution system operation can continue without any power interruption. Not all arcing earth faults can be self-extinguished. Whether a fault arc is self-extinguished or not depends mainly on the fault current magnitude and the recovery voltage (Hänninen et al. 1998). Consequently, the possibility of self-extinction is an additional reason to keep the earth fault current low in systems consisting exclusively or partly of overhead lines.

Chapter 3

Earth fault representation

During an earth fault in an electrical distribution network only one or two of the phases are connected to earth. The same conditions do not apply to all three phases, earth faults are thus unsymmetrical faults and the faulted systems are unsymmetrical systems. Unsymmetrical systems cannot be represented by single-phase equivalents, which are generally used to simplify analysis of symmetrical systems. They can however be modelled by use of symmetrical components and sequence networks. The use of symmetrical components is a mathematical method that is based on a change of the system of coordinates. It involves a transformation from phasor coordinates to the sequence coordinates a_1 a_2 and a_0, showed in Figure 3.1.

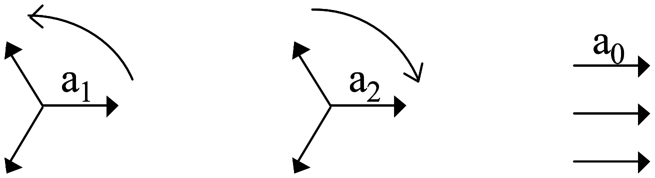

Figure 3.1 The positive, negative and zero sequence coordinate bases each consists of a set of three phasors.

The following brief description of symmetric components and sequence networks is based on texts by P. Anderson (Anderson 1995) and E. Lakervi and E.J. Holmes (Lakervi et al. 2003).

Unsymmetrical fault analysis is performed by transforming the three-phase network into positive, negative and zero sequence networks. The sequence networks can each be represented by a two-terminal network. The positive, negative and zero sequence two-terminal equivalents are shown in Figure 3.2. In three-phase systems, all voltages are generated in the positive sequence network and consequently, the negative and zero sequence two-terminal networks only consist of the equivalent impedances Z_{eq}.

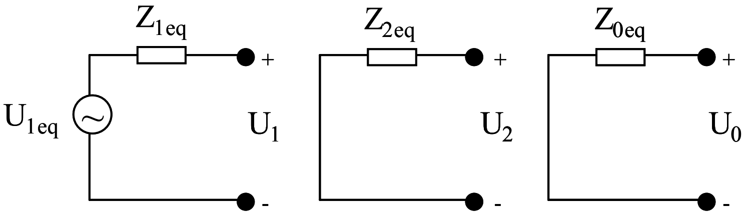

Figure 3.2 Positive, negative and zero sequence networks representing a three-phase distribution system.

Figure 3.3 shows a series connection of the sequence networks, which represents a single-phase earth fault.

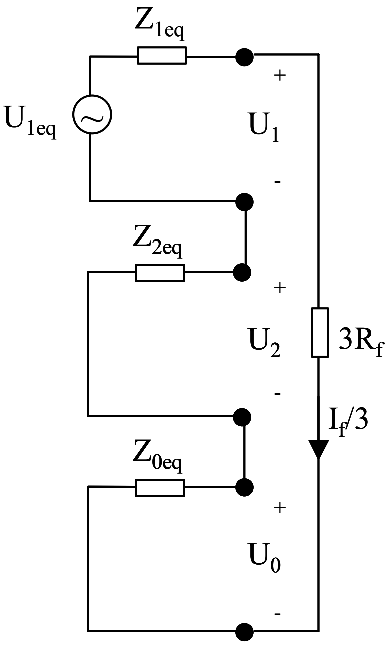

Figure 3.3 Positive, negative and zero sequence networks, connected to represent an earth fault.

During an earth fault, the three sequence currents equal each other at the fault location. The total fault current I_f is the sum the sequence currents and thereby three times the positive, negative or zero sequence current. The fault impedance R_f must be multiplied by three to be properly represented in the sequence network connection.

3.1 Transmission line representation

For the sequence networks to correctly represent a power system, the power system components must be adequately modelled in the networks. The necessary complexity of the component models depends on what kind of analysis the networks shall be used for. Within this work, the networks shall mainly be used for fundamental frequency analysis.

In this work, all transmission lines are represented by pi-sections. As shown in Figure 3.4 the pi-sections consists of one series impedance, Z_π, and two shunt admittances, Y_π, that represent the distributed series impedance and shunt capacitance of the transmission line. The use of pi-sections is a relatively simple way to model distribution feeders. It is adequate for fundamental frequency analysis but do not properly represent the transmission lines in most transient analysis (Lefebvre 1999).

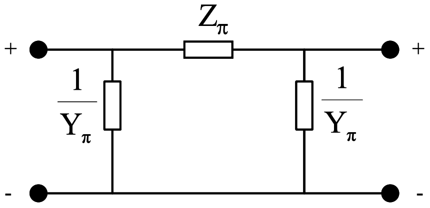

Figure 3.4 Pi-section two-terminal equivalent of transmission line

In sequence network analysis, the transmission lines are represented by positive, negative and zero sequence pi-sections that consist of positive, negative and zero sequence series impedance and shunt admittances. The series impedances and shunt admittances are derived from the properties of the transmission line.

In conventional power systems consisting of overhead lines and short cables, the zero sequence parameters control the earth fault behaviour and the positive and negative parameters can therefore be neglected (Lakervi et al. 2003).

3.2 Overhead lines

The zero sequence series impedance and shunt admittances of an overhead line pi-section shall represent the distributed (per unit of length) series resistance, r, and inductance, l, of the transmission line, and the distributed (per unit of length) shunt capacitance, c, between phase and earth. The equivalent series and shunt impedance in pi-sections that represent short overhead lines can be modelled as lumped values of the distributed variables (transmission line length d):

$$\begin{aligned} Z_\pi &= R + j\omega L = r \cdot d + j\omega l \cdot d \\ \frac{1}{Y_\pi} &= \frac{2}{Y} = \frac{2}{j\omega C} = \frac{2}{j\omega c \cdot d} \end{aligned} \tag{3.1}$$

For a long overhead line to be correctly modelled by one single pi-section, the equivalent series impedance and shunt admittance shall be calculated by use of correction factors (Glover et al. 2002):

$$\begin{aligned} g &= \sqrt{z \cdot y} \\ G &= g \cdot d \\ Z_\pi &= Z \frac{\sinh G}{G} \\ Y_\pi &= \frac{Y}{2} \frac{\tanh G/2}{G/2} \end{aligned} \tag{3.2}$$

The correction factors are frequency dependent and easily calculated in fundamental frequency analysis. An alternative to the use of correction factors is to model one long transmission line by several pi-sections connected in series.

3.3 Cables

The distributed zero sequence parameters of cables differ substantially from those of overhead lines. The cable resistance is comparable to the overhead line resistance. The series impedance is half and the shunt capacitance is between approximately 50 and 100 times that of overhead lines (Elforsk 2006).

Both series impedance and shunt capacitance is considered proportional to cable length. The series impedance of short cables is therefore small in relation to the shunt impedance. If the cables are short enough, the series impedance is negligible and the shunt capacitance alone makes up the pi-section representation of the cables, see for example (Lehtonen et al. 1996) and (Lakervi et al. 2003). Since the length of the cable feeders in conventional distribution systems is limited to a few kilometres, it has become common practice to neglect cable feeder series impedance in distribution system analysis.

Chapter 4

Earthing and earth fault protection

The series impedance and shunt capacitance of the transmission lines are important to, but do not alone determine, the earth fault behaviour. Instead, there are components that are connected to the systems with the only purpose to control the earth fault behaviour.

The distribution system earthing is the combination of the components that are used to control the behaviour of an unsymmetrical system. In practise, the system earthing consists of the connections between transformer neutral points and earth. The connections, i.e. the *neutral point equipment*, can differ between different transformers in the same system.

The connections influence the zero sequence equivalent impedance of the system and by that, the unsymmetrical fault current. The fault current in its turn determines the voltage at the transformer neutral, i.e. the *neutral point displacement voltage*.

The system earthing is designed to limit the maximum earth fault current, in order to avoid dangerous step and touch voltages. At the same time, it must also see to that fault currents and displacement voltages are high enough to facilitate high-impedance earth fault detection. In order to achieve this, different earthing designs must be used depending on the capacitive strength of the system. Since it is the type and the length of the distribution lines that determine the capacitance of the system, they are of vital importance to the choice of system earthing design.

For a thorough introduction to conventional system earthing analysis, see for example (Lehtonen et al. 1996) or (Lindahl 2006), which have served as main references for section 4.1 to 4.3 and 4.5.

4.1 Isolated neutral systems

Provided the safety requirements are fulfilled, the system earthing shall be designed to keep associated costs as low as possible. The easiest and cheapest method for system earthing is to leave the transformer neutral points isolated. This is the preferred earthing method in Swedish MV systems but the method will only assure safety requirement fulfilment in systems with limited capacitive connection to earth. Figure 4.1 shows an earth fault in an isolated neutral system.

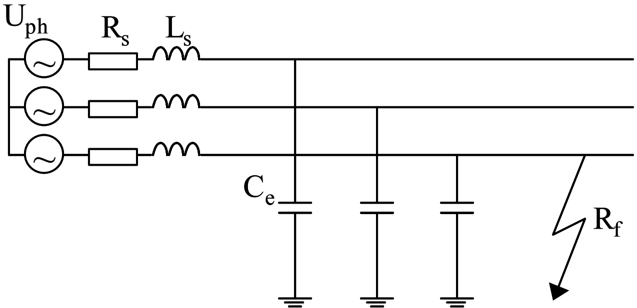

Figure 4.1 Earth fault in a system with an isolated neutral

In conventional systems consisting of overhead lines and short cables, the series impedance is very small compared to the shunt impedance and does not influence the earth fault behaviour. It can therefore be neglected in the three phase equivalent circuit shown in Figure 4.2 and the equivalent sequence network, shown in Figure 4.3.

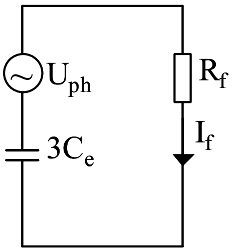

Figure 4.2 Equivalent circuit of earth fault in system with isolated neutral.

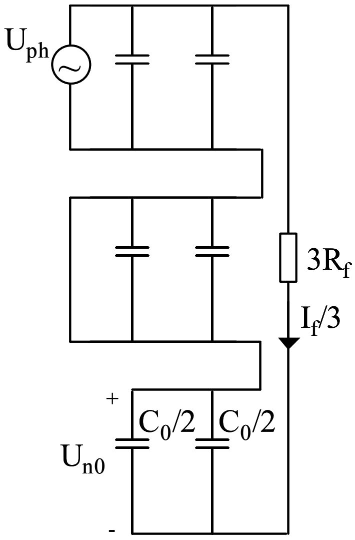

Figure 4.3 Sequence network equivalent of earth fault in isolated neutral system. The zero sequence capacitance, C_0, is equal to the capacitance between phase and earth, C_e.

Earth fault current and neutral point displacement voltage

The fault current and the neutral point displacement voltage can be derived from the equivalent circuit in Figure 4.2 or the sequence network equivalent in Figure 4.3.

Both the current and the voltage reach their maximum values during a solid earth fault, i.e. when the fault resistance is zero. If the fault resistance is negligible, the entire pre fault phase to earth voltage will be applied across the capacitance of the system and hence become the neutral point displacement voltage. The fault current is limited only by the phase to earth capacitance (zero sequence capacitance if the sequence network equivalent is used for derivation):

$$I_f = j\omega 3C_e U_{ph} = jI_C \tag{4.1}$$

$$I_f = 3I_0 = 3j\omega C_0 U_{ph} = jI_C \quad (4.2$$

The fault current is proportional to the total capacitive connection to earth. If the capacitance of the system is strong, the magnitude of the fault current will therefore be large and possibly dangerous. If the maximum earth fault current is considered dangerous, an isolated neutral system is not sufficient to fulfil the safety regulations and a different earthing method is required.

The voltages between the neutral point and the healthy phases are not influenced by the earth fault. Figure 4.4 shows how the magnitudes of the voltages of the healthy phases therefore equal the pre fault phase-to-phase voltage magnitude.

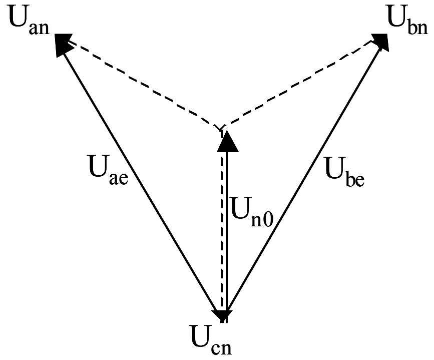

Figure 4.4 Voltage phasors during solid earth fault in isolated system. The neutral point displacement voltage equals the pre fault phase to earth voltage U_{cn} and the voltage of the healthy phases the pre fault phase-to-phase voltages.

The presence of a fault resistance increases the equivalent impedance of the system. This decreases the magnitude of the fault current as well as the magnitude of the neutral point displacement voltage.

The fault resistance adds a resistive part to the equivalent impedance and the earth fault current therefore consists of a resistive as well as a reactive component:

$$I_f = I_R + jI_C = \frac{R_f (3\omega C_0)^2 \cdot U_{ph}}{1 + (R_f 3\omega C_0)^2} + j\frac{3\omega C_0 \cdot U_{ph}}{1 + (R_f 3\omega C_0)^2} \tag{4.3}$$

Since there is a voltage drop across the fault resistance, the entire pre fault phase voltage is not applied across the system capacitance. The neutral point displacement voltage does not equal the pre fault phase voltage but is instead determined by the relation between the zero sequence impedance and the fault resistance:

$$U_{n0} = U_{ph} \frac{\frac{1}{j\omega C_0}}{\frac{1}{j\omega C_0} + 3R_f} \tag{4.4}$$

Even though the neutral point displacement voltage does not reach the pre fault phase voltage value, it differs from zero, and the magnitude of the voltage of the healthy phases might still exceed the pre fault values, see Figure 4.5. The phase and the magnitude of the neutral point voltage and the voltage across the fault resistance depend on the phase and magnitude of the earth fault current, and the fault resistance.

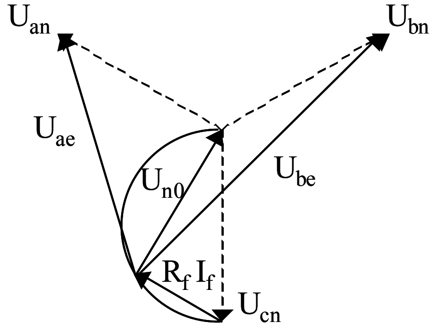

Figure 4.5 Voltage phasor diagram for an earth fault in an isolated neutral system. The neutral point displacement voltage and the voltage of the healthy phases depend on the fault resistance.

Fault detection

If the unsymmetrical current and the neutral point displacement voltage measured during earth faults differ sufficiently from normal operation values, they can be used to detect earth faults in the system. Typically, over voltage relays are used to detect the neutral point displacement voltage and directional residual over current relays are used for selective fault detection.

The relay settings, i.e. the relay operation thresholds, decide the sensitivity of the earth fault detection. Since high-impedance faults give relatively low fault currents and neutral point displacement voltages, high-impedance fault detection requires low relay operation thresholds. However, there are always natural unbalances in the systems. Natural unbalances give rise to a neutral point displacement voltage and unsymmetrical currents equivalent to those of very high-impedance faults. The voltage and currents can cause unwanted relay operation during normal operation if the thresholds are set too low.

According to the Swedish regulations, all earth faults with fault resistance below 3 kΩ (5 kΩ) shall be detected in systems that consists partly or entirely of overhead lines (ELSÄK 2008:1). In order to find a balance between desired high-impedance fault detection and avoidance of unwanted relay operation there must be a margin between the high-impedance fault current and the current due to natural unbalances.

As seen in Figure 4.6, the threshold margin (difference between 5 kΩ fault and very high-impedance faults) is larger in systems with strong capacitive connection to earth than in systems with weaker capacitance and consequently sensitive earth fault detection in isolated neutral systems requires a certain capacitive strength. If an acceptable balance between the desired detection and natural unbalances cannot be reached, a different earthing method is required.

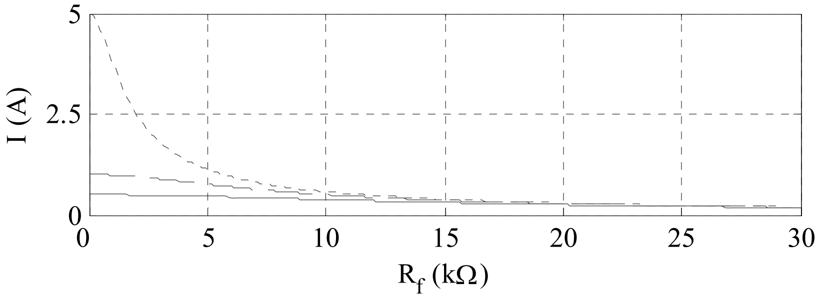

Figure 4.6 Calculated earth fault current for faults with varying fault resistance and different capacitive connection to earth. The capacitive connections of the systems corresponds to solid earth fault currents of 5 A (dotted), 1 A (dashed) and 0.5 A (solid line).

Isolated neutral earthing might lead to high fault currents in systems with very strong capacitance and is therefore not a suitable earthing method in systems with extensive use of cable. As it might also lead to insufficient fault detection in systems with very weak capacitance, it is neither suitable for system earthing in small systems consisting of overhead lines.

4.2 Resistance earthed systems

In order to facilitate high-impedance earth fault detection in systems with weak capacitive connection to earth, the difference between high-impedance earth fault currents and voltages, and those during normal operation must be increased. One way to increase the margin between high-impedance earth fault currents and currents due to normal operation unbalances is to connect a neutral point resistance to the neutral points of some of the transformers in the system. Figure 4.7 shows an earth fault in a system with a resistance earthed neutral.

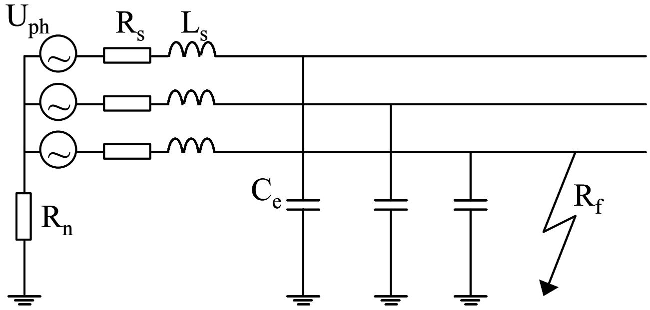

Figure 4.7 Earth fault in a network with a resistance earthed neutral.

Figure 4.8 shows the three phase equivalent circuit and Figure 4.9 the corresponding sequence networks equivalent. Since conventional distribution systems are assumed, the series impedance is neglected in the equivalent circuits. Since the neutral point resistance is parallel to the equivalent capacitance of the system, it decreases the magnitude of the resulting equivalent impedance and shifts its phase. These changes of equivalent system impedance magnitude and phase influence both the low and the high-impedance earth fault behaviour of the system.

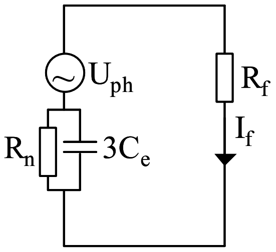

Figure 4.8 Equivalent circuit of an earth fault in resistance earthed system

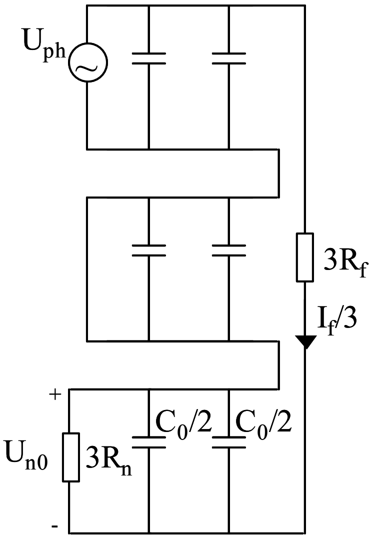

Figure 4.9 Sequence network equivalent of an earth fault in a resistance earthed system.

Earth fault current and neutral point voltage

The maximum earth fault current in resistance earthed system consists of a resistive as well as a reactive component:

$$I_f = I_R + jI_C = \frac{U_{ph}}{R_n} + j3\omega C_e U_{ph} \tag{4.5}$$

In overhead line systems with weak capacitive connection to earth, the capacitive shunt reactance is very large compare to the parallel neutral point resistance and the maximum earth fault current is therefore determined almost exclusively by the neutral point resistance:

$$\frac{1}{R_n} >> 3\omega C_e \Rightarrow I_f \rightarrow \frac{U_{ph}}{R_n} \tag{4.6}$$

Fault detection

A fault resistance reduces the magnitude of the fault current. In resistance earthed systems with weak capacitive connection to earth, the phase of the current is however unaffected and the current solely resistive:

$$I_f = \frac{U_{ph}}{R_n + R_f} \tag{4.7}$$

Since the neutral point resistance decreases the zero sequence impedance, the amplitude of the earth fault current will look like the amplitude of the earth fault current in isolated neutral systems with much higher capacitive connection to earth.

Figure 4.10 shows that the margin between the 5 kΩ fault current threshold and the current due to natural unbalances is considerable larger in resistance earthed systems than in isolated neutral systems with corresponding capacitive connection to ground. Consequently, small overhead line systems with a weak capacitive connection to earth can be resistance earthed in order to facilitate earth fault detection.

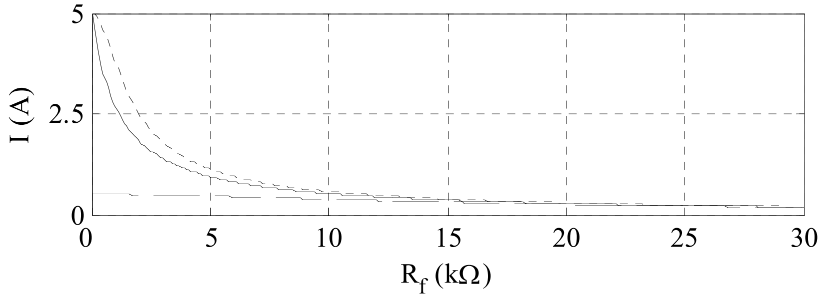

Figure 4.10 Calculated earth fault current magnitude for different fault resistances in a resistance earthed system (solid line) and an isolated system with weak capacitive connection to earth (dashed line) and an isolated system with a stronger capacitive connection to earth (dotted line).

4.3 Resonant earthed system

In large overhead line or cable systems with isolated neutrals, the problem is instead a strong capacitive connection to ground and hence extensive earth fault currents. In order to fulfil required safety regulations the large capacitive earth fault current must somehow be decreased. In resonant earthed systems, the earth fault current is decreased by use of inductive neutral point reactors called Petersen coils. The Petersen coils, which are connected between an arbitrary number of the transformer neutral points and earth, decrease the resulting capacitive strength of the system.

Figure 4.11 shows an earth fault in a system with a resonance earthed neutral.

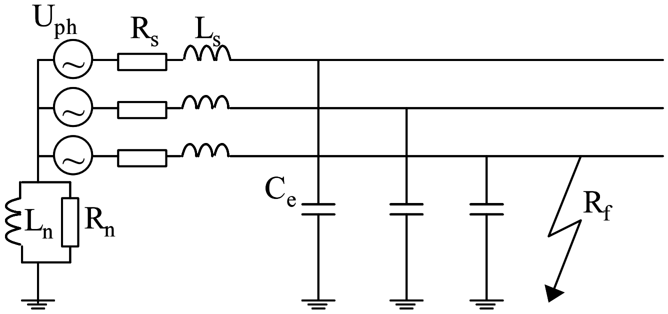

Figure 4.11 Earth fault in a network with a resonance earthed neutral.

Figure 4.12 shows the corresponding sequence network equivalent in a system with negligible series impedance.

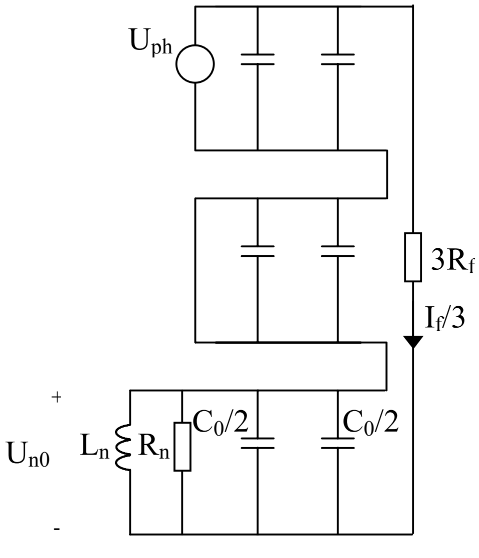

Figure 4.12 Sequence network equivalents of earth fault in resonance earthed system.

The equivalent reactance of a resonance earthed system is the parallel connection of the capacitance to earth and the neutral point inductance:

$$X_0 = \frac{\frac{1}{3\omega C_0} \cdot \omega L_n}{\frac{1}{3\omega C_0} + \omega L_n} = \frac{\omega L_n}{1 + \omega^2 L_n 3C_0} \tag{4.8}$$

If the size of the Petersen coil reactance is of the same size as the capacitive reactance of the system, the resulting impedance is very large and the earth fault current small at the fault location. In order to facilitate earth fault detection, the neutral point reactor can be combined with a neutral point resistor. The equivalent impedance of the system is then the parallel connection of the reactance and the neutral point resistance:

$$Z_0 = \frac{R_n \cdot j \cdot X_0}{R_n + j \cdot X_0} \tag{4.9}$$

Earth fault current and neutral point voltage

The earth fault current generated in the Petersen coil is inductive and the phase therefore directed opposite to that of the capacitive current generated by the distributed capacitance of the transmission lines. The resistive component of the earth fault current is determined by the neutral point resistance and resistive losses in the Petersen coil. The coil losses increase with the coil size, and are in most cases negligible compared to the neutral point resistor:

$$I_f = I_R + j \cdot I_C - j \cdot I_L = \frac{U_{ph}}{R_n} + j \cdot 3\omega C_0 \cdot U_{ph} - j \cdot \frac{U_{ph}}{\omega L_n} \tag{4.10}$$

A fault resistance increases the equivalent impedance of the system and by that reduces the earth fault current and the neutral point displacement voltage:

$$I_f = \frac{U_{ph}}{Z_0 + R_f} = \frac{U_{ph}}{\frac{R_n \cdot j \cdot X_0}{R_n + j \cdot X_0} + R_f} \tag{4.11}$$

$$U_{n0} = U_{ph} \frac{Z_0}{Z_0 + R_f} \tag{4.12}$$

The selective detection of earth faults in resonance earthed systems is typically carried out as in resistance earthed systems. Directional residual over current relays measure the resistive part of the earth fault current and voltage relays measure the neutral point displacement voltage.

Petersen coil tuning

If the size of the Petersen coil is selected so that the magnitude of the inductive current exactly compensates that of the capacitive current, the maximum resulting earth fault current will only consist of a resistive part:

$$\frac{1}{\omega L_n} = 3\omega C_0 \Rightarrow I_f \to \frac{U_{ph}}{R_n} \tag{4.13}$$

A fault resistance decreases the magnitude of the solely resistive fault current:

$$\frac{1}{\omega L_n} = 3\omega C_0 \Rightarrow X_0 \to \infty \Rightarrow I_f \to \frac{U_{ph}}{R_n + R_f} \tag{4.14}$$

If the Petersen coils are dimensioned to generate an inductive current that is slightly smaller than the current necessary for total compensation the resulting fault current consists of a small capacitive component as illustrated in Figure 4.13. If the compensation degree is less than 100 %, the system is said to be under compensated. In many parts of Europe, the compensation degree might instead exceed 100 % and those systems are hence over compensated.

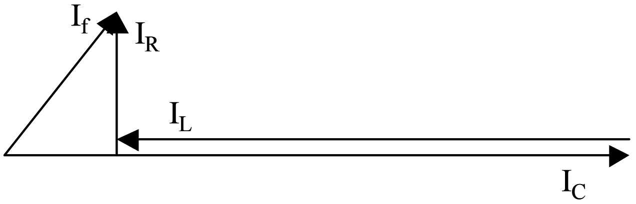

Figure 4.13 Current phasors in an under compensated resonant earthed system

A slight under or over compensation is often necessary to avoid high relay thresholds and unwanted operation due to natural unbalances in the systems (Lindahl et al. 1990). The influence of the coil tuning on the maximum earth fault current depends on the capacitance of the system. A decrease of the coil inductance (over compensation) will to a higher degree influence the fault current than corresponding compensation coil inductance increase (under compensation) (Zamora et al. 2004). In most systems, a slightly under or over dimensioned compensation coil, combined with a neutral point resistances of adequate size, will keep the resulting earth fault current low enough to facilitate arc fault self-extinction, and at the same time enable sufficient earth fault detection.

Conventional Petersen coil tuning is based on measurements of the neutral point voltages during normal operation. This can be done since natural unbalances give rise to a neutral point displacement voltage that reaches its maximum when the size of the Petersen coil reactance equals that of the system capacitance. Figure 4.14 shows a distribution system tuning curve based on simulated neutral point voltage values during an earth fault on the HV to MV transformer busbar. In this particular example, a Petersen coil with an inductance of 205 mH generates an inductive current that corresponds to the capacitive current of the system and therefore result in maximum neutral point displacement voltage.

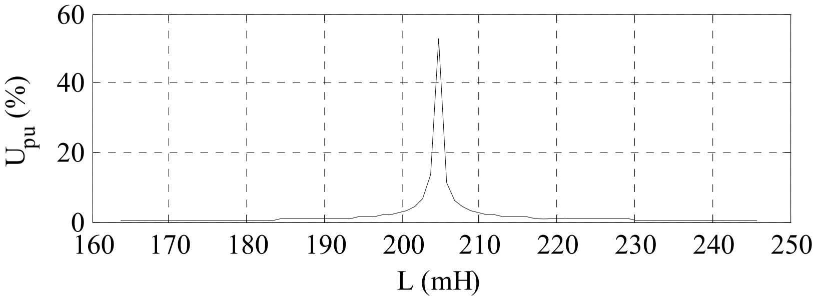

Figure 4.14 Petersen coil tuning curve based on simulated neutral point voltages. The maximum voltage (resonance) is reached for a coil inductance that corresponds to the capacitive reactance of the system.

In many cable systems, the natural unbalances are small and an artificial unbalance might therefore be required in order to facilitate the tuning (Leikermoser et al. 2007). The unbalance is normally injected at the transformer neutral point.

4.4 Distributed compensation

The Petersen coils can be tuned so that the resulting reactive current is very small at the fault location, but the inductive and the capacitive current are generated at different locations and the inductive current will not compensate for the capacitive current in all parts of the system. The separate inductive and capacitive current flows are shown in Figure 4.15.

The capacitive current flows through the capacitance between phases and earth, but it also flows through the series impedance of the transmission lines. In conventional systems consisting of overhead lines and short cables, the series impedance can be neglected and the reactive current flows do therefore not influence the system behaviour. In systems with non-negligible series impedance, the situation is quite different.

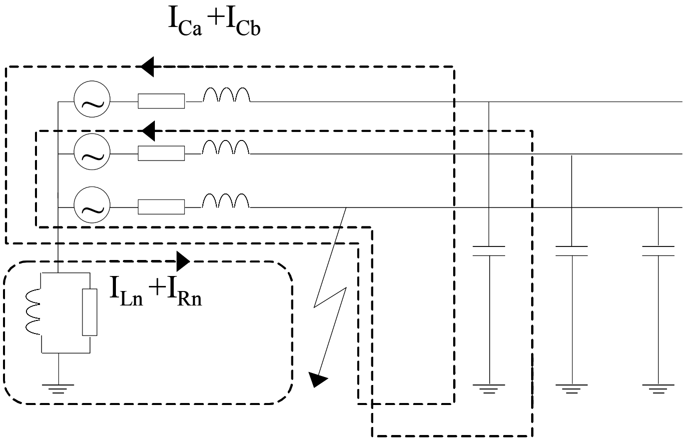

Figure 4.15 Earth fault current flow in resonant earthed system consisting of one three-phase transmission line (Lehtonen et al. 1996). The inductive and the capacitive current are generated at different locations and flows separately in the system.

The transmission line series impedance has a resistive part. Consequently, the equivalent impedance of the system is partly resistive and the earth fault current that flows through the lines and through the distributed capacitive coupling to earth has a resistive component. Figure 4.16 shows the sequence network equivalent of a busbar earth fault in a resonance earthed system with non-negligible series impedance. The series impedances influence the equivalent positive, negative and zero sequence impedance so that each consists of a resistive as well as a reactive component, and hence the earth fault current has a resistive part. The resistive earth fault component cannot be compensated for by use of Petersen coils. A different type of system earthing than conventional resonant earthing is therefore necessary if the resistive current component endangers personal safety or in other ways violates the regulations (ELSÄK-FS 2008:1).

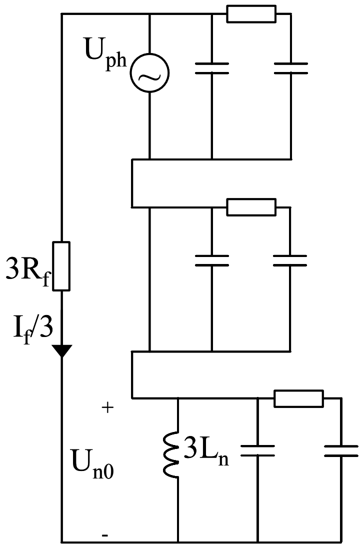

Figure 4.16 Equivalent circuit of busbar earth fault in resonant earthed system consisting of one long cable feeder. The series impedance is non-negligible.

One earthing method that can be used to decrease the resistive part of the earth fault current is distributed compensation. In systems with distributed compensation, a number of Petersen coils are located along the transmission lines. Since the inductive and the capacitive fault currents are generated close to each other, the reactive power flow and the resistive losses are considerably smaller than what is the case in traditionally resonance earthed systems.

Figure 4.17 shows the sequence network equivalent of a busbar earth fault in a system with distributed compensation. The local Petersen coils and the zero sequence capacitance together form the zero sequence shunt impedance of the system. If the coils are dimensioned to compensate for the capacitive current generated in the system, and the distance between the coils is limited, the total shunt impedance is very large and the influence of the series impedance can therefore be neglected.

Even with negligible series impedance, there is a resistive fault current component. This is due to losses in the Petersen coils. The Petersen coil losses are proportional to the amount of inductive current generated by the coils and significantly lower than the resistive losses due to reactive current transportation in systems with conventional resonant earthing.

An additional benefit associated to distribute compensation is that disconnection of part of the network will disconnect a corresponding amount of compensation.

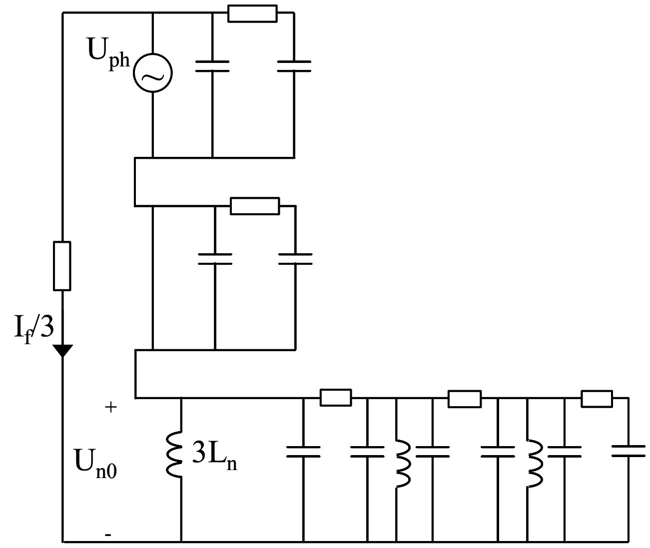

Figure 4.17 Sequence network equivalents of an earth fault on the HV to MV transformer busbar in a system with distributed compensation.

4.5 Solidly earthed systems

A system in which at least one of the transformer neutrals is directly connected to earth is called a solidly earthed system (IEC 2008). During an earth fault in a solidly earthed system the capacitive connection between phase and earth is bypassed as shown in Figure 4.18. Figure 4.19 shows the corresponding equivalent circuit.

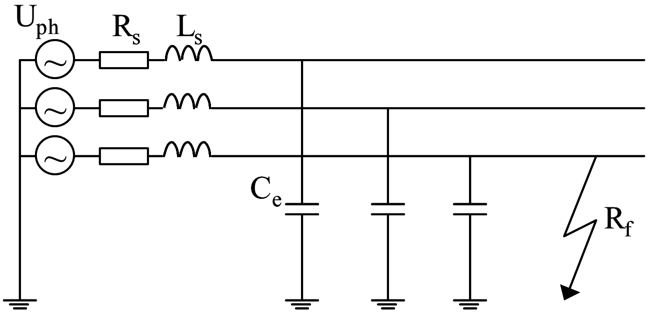

Figure 4.18 Earth fault in solidly earthed system and corresponding equivalent circuit

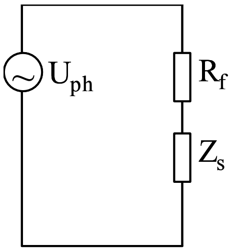

Figure 4.19 Equivalent circuit of earth fault in solidly earthed system.

The fault current in solidly earthed systems is limited only by the series impedance and the fault impedance and earthing resistance and the fault can be considered a short-circuit. In most systems, the series impedance is small and a low-impedance earth fault will therefore result in a very large current. The main advantage of solidly earthed systems is limited over voltages, which makes the earthing design common in HV systems. Solid earthing is not used in Swedish MV systems.

Chapter 5

Long cable feeders

The amount of underground cable in Swedish rural distribution systems has increased considerably since the 2005 hurricane Gudrun (E.ON 2008). The resulting new rural networks combine the long line sections of the traditional rural network that they replace with the use of cable, common in urban networks. The systems thereby differ from traditional rural systems consisting of long overhead lines as well as from traditional urban systems consisting of several relatively short cable feeders. The introduction of long cable feeders might influence the distribution system analysis and operation. In the following chapters, conventional distribution system earth fault analysis is re-evaluated, taking distribution systems with long cables into consideration.

Distribution systems with long cables are new also in an international perspective and very little research has therefore been published in the field. However, there are recent publications on extensive use of underground cable that do not focus on long cables. The authors argue that neglecting the series impedance in systems consisting of extensive amount of underground cable can lead to incorrect estimations of earth fault currents and over voltages (Gatta et al. 2007) (Obkircher et al. 2006).

5.1 Conventional earth fault analysis assumptions

Conventional distribution system earth fault analysis and planning procedures are based on a number of simplifying assumptions. Most of these assumptions follow from cables being represented by capacitance only:

- The total cable length determines the earth fault behaviour of the system. It does not make any difference if the total length is made up by a few long or many short cables.

- The earth fault current is solely capacitive and proportional to total cable length. The entire earth fault current can therefore be compensated for by use of a Petersen coil. The size of the coil can be dimensioned from cable data and its resistive losses (resistive current) are proportional to the inductive current generated in the coil.

- The neutral point displacement voltage in a tuned system is determined exclusively by the neutral point resistance and fault resistance.
- The fault location does not influence the earth fault behaviour of the system.

In this chapter, the validity of these assumptions for systems with long cables is assessed through time simulations.

The nominal voltage of the simulated systems is 10 kV, the capacitance to earth is 0.33 μF per km and phase and the total cable length is 80 km. The total capacitance of the system is thereby 79.2 μF. The zero sequence series resistance and inductance are 1.5 Ω per km and 2 mH per km respectively.

First, the earth fault behaviour of a distribution system that consists of 10 relatively short cable feeders (each 8 km) is simulated. The simulated earth fault behaviour during a fault on the busbar and during a fault at the end of a cable feeder is shown in Table 5.2. The table also shows the expected values calculated according to the above assumptions.

Table 5.1 Simulated and expected earth fault behaviour in cable systems consisting of short cables. The Petersen coils have 2 % resistive losses.

Studied quantity	**Simulated results busbar fault**	**Simulated results end of feeder fault**	**Expected results**
Solid earth fault current	144 A ∠90 °	144 A ∠90 °	144 A ∠90 °
Petersen coil tuning	128 mH	128 mH	128 mH
Compensated fault current	3.0 A ∠0 °	3.0 A ∠0 °	2.9 A ∠0 °
Neutral point displacement voltage	5.77 kV	5.77 kV	5.77 kV
5 kΩ fault neutral point displacement voltage	1.61 kV	1.61 kV	1.66 kV

The simulated fault behaviour is in accordance with the expected results:

- The earth fault behaviour does not depend on fault location. Provided an isolated neutral and no fault resistance, the earth fault current is solely capacitive and reaches 144 A for busbar faults as well as for end of line faults.

- The entire capacitive earth fault current can be compensated by a 128 mH coil, so that only the resistive current due to losses in the coil remains.
- As expected, the neutral point voltage level (simulated busbar voltage) during a 5 kΩ fault is approximately 28 % (1.61/5.77 kV) of the pre fault phase voltage, and can most likely be used for fault detection.

This suggests that conventional power system analysis assumptions are valid for systems with cables of limited length.

Now, the earth fault behaviour of a system that consists of one long 80 km cable feeder is instead simulated. Since the total cable length, the capacitance and the nominal voltage remain the same as in the above simulations, the expected results remain the same. The simulated earth fault behaviour during an earth fault on the busbar and during an earth fault at the end of the cable is shown in Table 5.2. The table also shows the expected results based on the conventional assumptions

Table 5.2 Simulated and expected earth fault behaviour in cable systems consisting of a long cable. The Petersen coils have 2 % resistive losses.

Studied quantity	**Simulated results busbar fault**	**Simulated results end of feeder fault**	**Expected results**
Solid earth fault current	152 A ∠68 °	133 A ∠80 °	144 A ∠90 °
Petersen coil tuning	132 mH	138 mH	128 mH
Compensated fault current	58 A ∠1.7 °	38 A ∠39 °	2.9 A ∠0 °
Neutral point displacement voltage	5.77 kV	4.26 kV	5.77 kV
5 kΩ fault neutral point displacement voltage	112 V	129 V	1.66 kV

The simulations show that the earth fault behaviour in systems consisting of long cables is different from the expected results and from that of systems consisting of short cables. The conventional assumptions valid for conventional systems consisting of short cables are not valid for systems consisting of long cables:

- The fault location does influence the earth fault current and the

Petersen coil tuning in systems that consists of long cables. In these examples the Petersen coil is tuned considering a busbar earth fault. The maximum earth fault current in an isolated neutral earthed system is 152 A during the busbar faults but only 133 A during the end of cable fault.

- The earth fault current is not solely capacitive but has a resistive part that cannot be compensated by use of the Petersen coil. The phase of the busbar fault current is 68° and the phase of the end of cable fault current is 80°.

- The neutral point displacement voltage (simulated busbar voltage) in tuned systems is not determined exclusively by the neutral point resistance and fault resistance. During a 5 kΩ fault the neutral point displacement voltage is in the order of 110-130 V, which is considerable lower than the expected 1.66 kV. The low values might make fault detection difficult.

It can thereby be concluded that not only the total cable length but also how it is arranged - the network structure - determine the earth fault behaviour in distribution systems with extensive use of cable.

In the following chapters, circuit theory and sequence network equivalents are used to explain the above results and gain an understanding of electrical distribution systems consisting of extensive amount of cable. In addition, further time simulations are presented to evaluate the results from the circuit analysis.

Chapter 6

Circuit analysis

The earth fault simulations presented in Chapter 5 show that distribution systems with long cables do not behave as conventional distribution systems, and that assumptions used for conventional earth fault analysis are not valid for analysis of distribution systems consisting of long cables. While the simulations show *how* the structure influences the earth fault behaviour, additional analysis is needed in order to understand *why*.

In this chapter, it will be explained why there is a difference between the fault behaviour in systems with different network structures, and why the fault location influences the earth fault behaviour in systems that consist of long cables. It will also be explained why there is a resistive earth fault current component in these systems and why the neutral point displacement voltage might be very low during high-impedance faults.

The use of circuit theory and sequence networks and symmetrical components allows for a straightforward analysis of unsymmetrical systems. It is a method commonly used in teaching as well as in research; see for example (Lakervi et al. 2003) (Anderson 1995) (Glower et al. 2002) (Gatta et al. 2007).

Circuit analysis is associated with certain simplifications. Simplifications are not altogether a bad thing; they are necessary in applied engineering. It is however important not to draw conclusions that are outside the validity range of the simplifications. In this work, the analysis is simplified to treat fundamental frequency and the obtained results are therefore valid for fundamental frequency behaviour. Transient earth fault behaviour is not treated in this work. This does not mean that cable systems are not associated with transients. Charge and discharge transients are proportional to the capacitance of the system and therefore large in systems consisting of extensive use of cable (Guldbrand 2006b). In addition, many cable systems are resonance earthed and thereby have earth fault current transients associated with compensation coils (Lehtonen et al. 1996).

6.1 Network representation

In sequence network analysis, electric equipment is represented by symmetric parameters. The derivation of the parameters that represent overhead lines is well documented, see for example (Anderson 1995), while the derivation of cable parameters is more diverse. In particular, the derivation of zero sequence impedance is complex and differs between different publications. For power cable zero sequence impedance derivation see for example (Henning) and (Andreou 2007).

The 10 kV underground cable and overhead line sequence parameters used throughout this work is listed in Table 6.1. These parameters are used in the analytical calculations as well as in computer simulations, unless differently stated. The cable and overhead line parameters are based on data from manufacturers (Nexans 2008) (Ericsson 2004) and parameters used in an Elforsk report on long distribution cables (Elforsk 2006). The cable data is in accordance with that of 95 mm^2 XLPE cables with circular conductors.

Table 6.1 Underground cable and overhead line sequence parameters

	Series resistance r	Series inductance l	Shunt capacitance c
Cable			
Positive and negative seq.	0.32 Ω/km	0.3 mH/km	0.33 μF/km
Zero seq.	1.5 Ω/km	2 mH/km	0.33 μF/km
Overhead line			
Positive and negative seq.	0.52 Ω/km	1.3 mH/km	9.95 nF/km
Zero seq.	0.67 Ω/km	6.4 mH/km	4.4 nF/km

In conventional earth fault analysis, cables are modelled by zero sequence capacitance only. This is, as explained in Chapter 3, accurate if the length of the cable is limited. If the cables are very long, the series impedance is much larger and the influence of the series impedance is thereby not necessarily negligible.

In order to find out for which cable lengths the solely capacitive approximation of cable representation is valid, the equivalent zero sequence impedance of cables modelled by capacitance only have been compared to that of cables modelled by pi-sections that include the series impedance.

Figure 6.1 shows the calculated zero sequence impedance of cables of varying length, as seen from the transformer busbar.

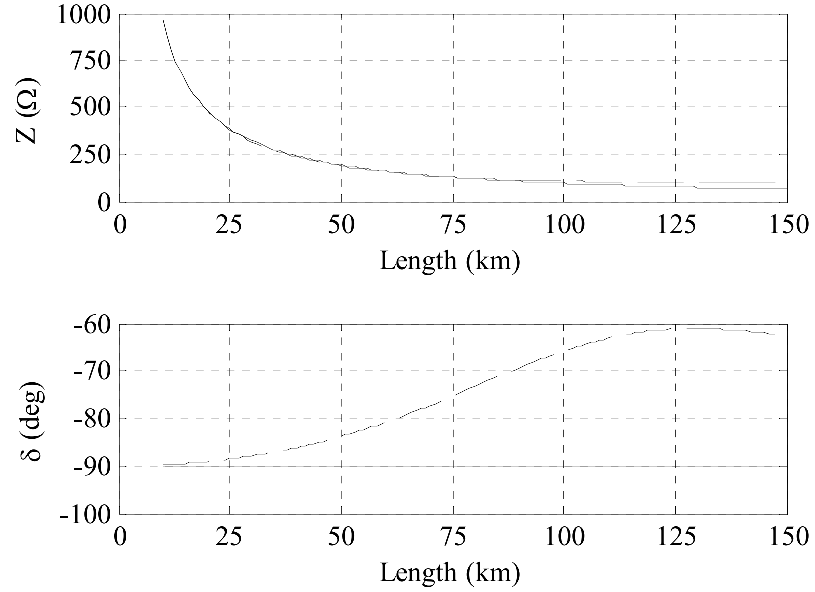

Figure 6.1 Magnitude and argument of the equivalent zero sequence impedance of cables modelled by pi-sections (dashed) and capacitance only (solid).

The series impedance does not influence the absolute value of the equivalent impedance considerably. It does however influence the argument. The argument of the impedance differs from -90°, which means the impedance consists of a resistive part as well as a reactive part. The resistive part thus clearly influences the fault behaviour. This confirms that common practise which ignores series resistance is insufficient for analysis of distribution systems consisting of long cable feeders.

As explained in Chapter 3, correction factors are commonly used in analysis of distribution systems consisting of long overhead lines. The correction factors are used to compensate for non-linear behaviour of the pi-section shunt capacitances and series impedance. The need of correction factors depends on the length of the transmission lines and their electrical parameters. Since the electric parameters of cables differs substantially from that of overhead lines, the non-linear behaviour of the shunt capacitance and the series impedance will influence the earth fault behaviour of cables that are considerable shorter than corresponding overhead lines.

Figure 6.2 shows the equivalent zero sequence impedance of cables represented by pi-sections modelled with correction factors and the equivalent zero sequence impedance of cables represented by pi-sections modelled without correction factors.

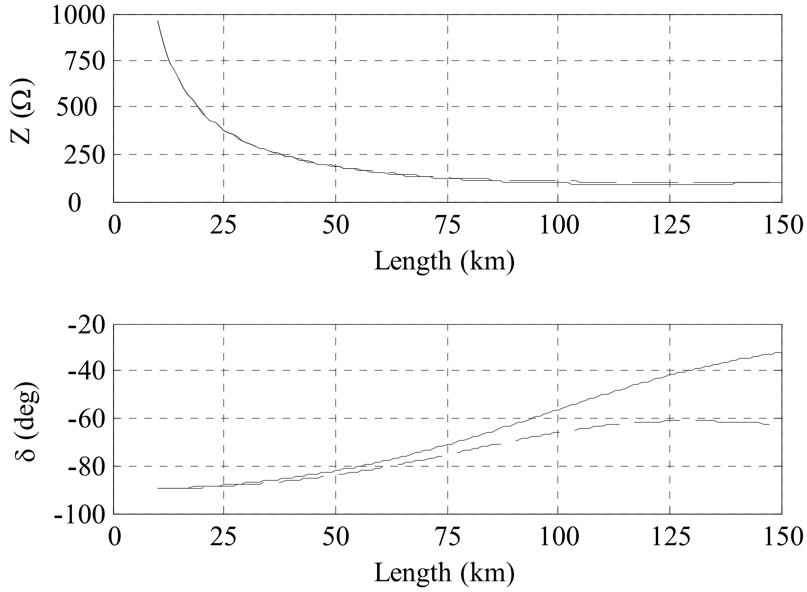

Figure 6.2 Absolute value and argument of the equivalent zero sequence impedance of cables modelled with (solid) and without (dashed) correction factors.

The correction factors influence the argument but not to any considerable extent the magnitude of the equivalent impedance. Correction factors are not required for pi-section representation of short cables, i.e. cables which lengths does not exceed 30 or 40 km. Longer cables are however not correctly represented if the correction factors are not included in the models.

The equivalent zero sequence impedance presented in Figure 6.1 and Figure 6.2 consists of a resistance in series with a reactance:

$$Z = R + jX \tag{6.1}$$

The equivalent impedance can however also be represented by an equivalent resistance R_p in parallel with an equivalent reactance X_p:

$$R_p = \frac{R^2 + X^2}{R} \tag{6.2}$$

$$X_p = \frac{R^2 + X^2}{X} \tag{6.3}$$

Figure 6.3 shows the parallel resistance and reactance that corresponds to the equivalent impedance in Figure 6.2.

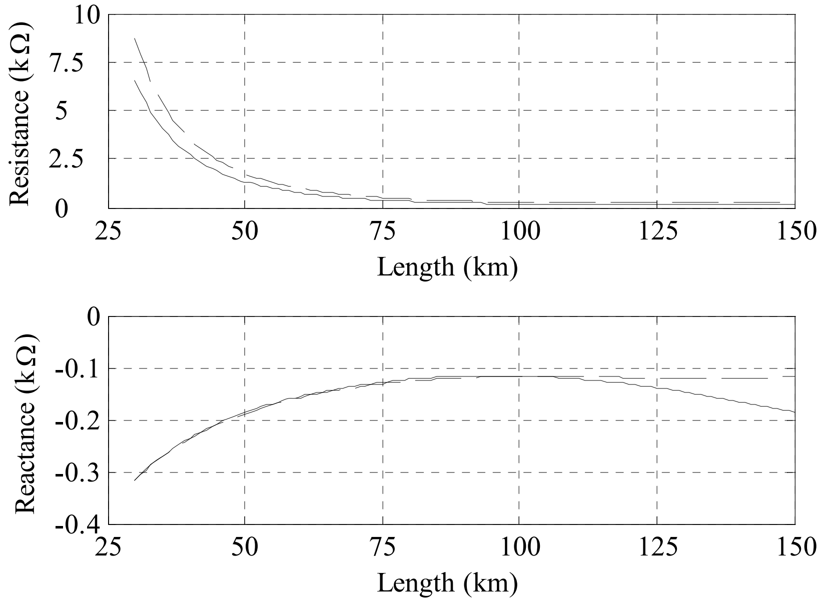

Figure 6.3 Equivalent parallel resistance and reactance of cables modelled with (solid line) and without (dashed) correction factors.

The equivalent resistance is very high for short cables, and the reactance is therefore dominating. However, as the length of the cable increases, the equivalent parallel resistance decreases and will start to influence the earth fault behaviour.

6.2 Network structure

In order to explain why the series impedance is not negligible in long cable feeders, we first have to understand the difference between system consisting of short cables and systems consisting of long cables.

Figure 6.4 shows the positive, negative and zero sequence networks of a conventional cable system consisting of four relatively short cable feeders. The feeders, each modelled by one pi-section, are connected to the same busbar and are thus in *parallel.* Distribution systems consisting of many short cables are common in urban areas, and this system will therefore be referred to as an *urban system.*

The impedances of the HV network and the transformer impedances, Z_{T1}, Z_{T2} and Z_{T0}, are not of importance to the understanding of the earth fault behaviour and are therefore set to zero in this analysis. They might however influence specific results and shall therefore be included if these are of interest.

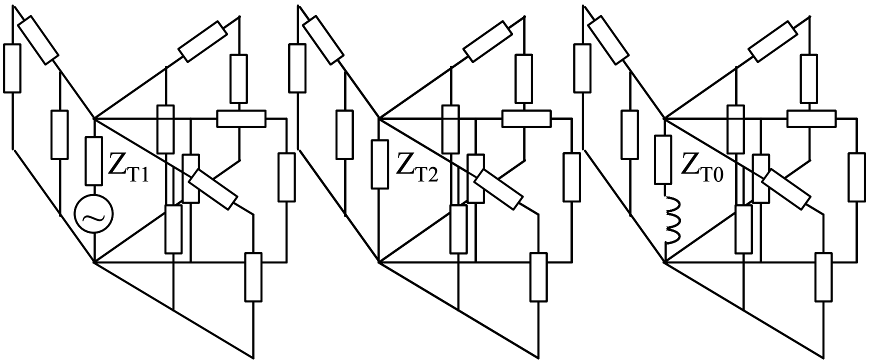

Figure 6.4 Positive, negative and zero sequence networks of a centrally compensated urban system consisting four short cables, $Z_{T1}= Z_{T2} = Z_{T0}= 0$. The inductance represents the compensation coil.

Figure 6.5 shows the positive, negative and zero-sequence networks of a system that consists of one long cable feeder. The four pi-sections and the total cable length are similar to that of the urban system in Figure 6.4, but the pi-sections are connected in *series* in order to represent the single long cable. Distribution systems consisting of a small number of long feeders are common in rural areas and this system will therefore be referred to as a *rural system.*

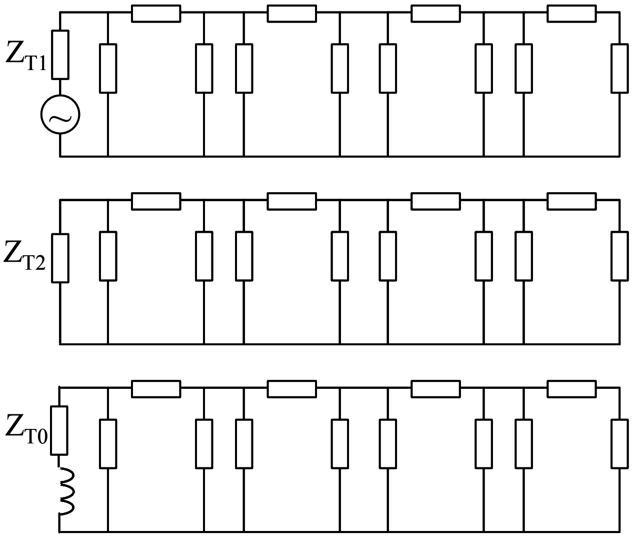

Figure 6.5 Positive, negative and zero-sequence networks of a centrally compensated rural system consisting one long feeder $Z_{T1}= Z_{T2} = Z_{T0}= 0$.

The main difference between the equivalent sequence impedances of urban and rural networks is that while the former consists of shunt capacitances, and series impedances connected in parallel, the latter consists of shunt capacitances connected in parallel and series impedances connected in series. The equivalent series impedance of systems consisting of a few long cable feeders is therefore larger than the equivalent series impedance of systems consisting of several short cables. This difference significantly influences the earth fault behaviour of the systems.

Busbar fault

First, we consider a fault on the busbar. The equivalent impedance, earth fault current and voltage rise all depend on the network structure. If there are several cables connected in parallel, the total equivalent impedance is considerably smaller than the impedance of an individual cable. The impedance of a relatively short cable feeder can be modelled by one small series impedance and two considerably larger capacitive impedances:

$$Z_{eq0(1)} = \left(\frac{1}{Y_{\pi 0}} + Z_{\pi 0} \right) // \frac{1}{Y_{\pi 0}} = \left(\frac{2}{j\omega C_0} + R_0 + j\omega L_0 \right) // \frac{2}{j\omega C_0} \qquad (6.4)$$

Since the equivalent impedance of n parallel feeders of equal length is one nth part of the impedance of each feeder, both the series impedance and the capacitive shunt impedance is one nth part of that of the individual cable feeders:

$$Z_{0eq(n)} = \frac{Z_{0eq(1)}}{n} = \frac{1}{n} \cdot \left(\frac{2}{j\omega C_0} + R_0 + j\omega L_0 \right) // \frac{1}{n} \cdot \frac{2}{j\omega C_0} \qquad (6.5)$$

The relation between the total capacitive shunt inductance and the total series impedance of the system is thereby equal to that of the individual feeders and since the lengths of the individual feeders are limited the influence of the total series impedance is negligible compared to the total capacitive shunt impedance.

The sequence networks in Figure 6.6 represent a busbar earth fault in an urban system with four relatively short cables. Neither the positive nor the negative sequence parameters influence the fault behaviour. Since the series impedance is negligible, there are no voltage drops along the cables and the zero sequence voltage is thereby equal all over the system.

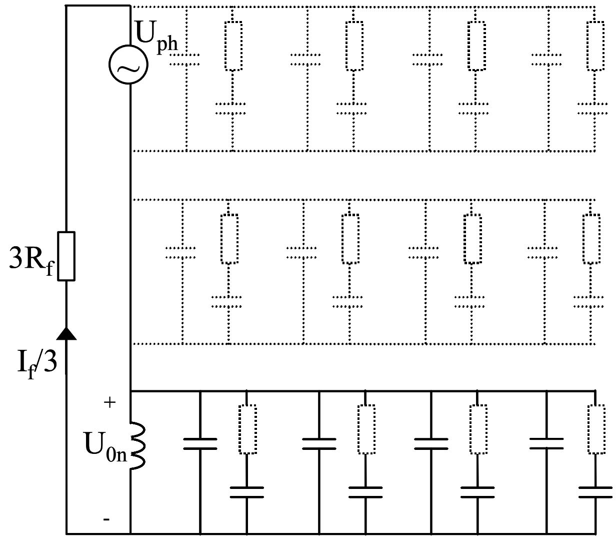

Figure 6.6 Sequence network equivalent representing an earth fault at the busbar in a resonance earthed urban system. The series impedance is negligible and the positive and negative sequences do not influence the fault behaviour.

Figure 6.7 show the same circuit redrawn in a simplified way. The equivalent impedance and the maximum earth fault current are solely capacitive. The magnitude of the current is proportional to the total cable length and the entire earth fault current can be compensated for by use of conventional resonance earthing.

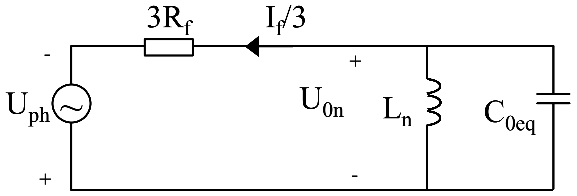

Figure 6.7 Equivalent circuit during an earth fault on the busbar in a resonance earthed urban system. The zero sequence voltage is equal to the neutral point displacement voltage in every part of the system.

A long cable feeder can instead be seen as a series connection of n short cables. Figure 6.8 shows a rural system with the same total length as the urban system in Figure 6.6.

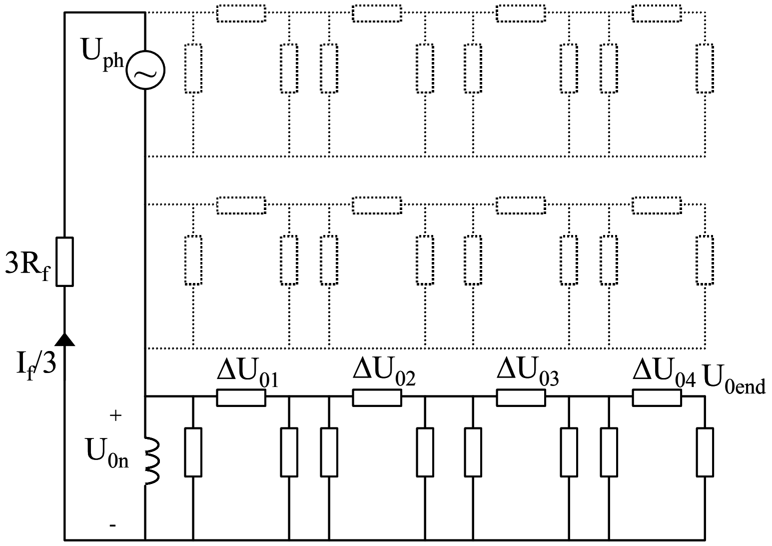

Figure 6.8 Sequence networks representing an earth fault at the busbar in a resonance earthed rural system. Neither the positive nor the negative sequence parameters influence the result (dashed).

The equivalent impedance of the long cables can be modelled by use of a corrected pi-section, in which the series and shunt impedances is n times that of the short cables, or recursively calculated by series connection of n short pi-sections:

$$Z_{0eq(i+1)} = \left(\left(Z_{0eq(i)} // \frac{2}{j\omega C_0} \right) + R_0 + j\omega L_0 \right) // \frac{2}{j\omega C_0} \qquad (6.6)$$

This means that the series impedance is in the order of n times that of the short cable, while the capacitive shunt impedance is approximately one nth part of that of a short cable:

$$\begin{aligned} Z_{0(n)} &\approx nZ_{0(1)} \\ \frac{1}{Y_{0(n)}} &\approx \frac{1}{nY_{0(1)}} \end{aligned} \qquad (6.7)$$

Since the series impedance increases and the capacitive shunt impedance decreases as the cable length increases, the series impedance of long cables is not necessarily negligible. Figure 6.9 shows the same circuit as in Figure 6.8, drawn in a simplified way. The series impedance adds a resistive part to the equivalent impedance of the system. Part of the earth fault current is therefore resistive and the earth fault current cannot be completely compensated for by use conventional resonant earthing.

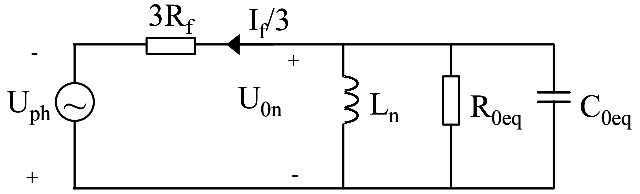

Figure 6.9 Equivalent circuit during an earth fault on the busbar in a resonance earthed rural system. The resistance and capacitance in the figure is the parallel impedance equivalents of the total cable impedance.

The zero sequence current causes complex voltage drops over the non-negligible zero sequence series impedances and the zero sequence voltage will therefore differ between different locations in the system. This is quite contrary to conventional cable system analysis, in which assumptions regarding negligible series impedance and equal zero sequence voltage in the entire system are common practice, see for example (Griffel et al. 1997) and (Messing 2001).

Next, calculations based on the above sequence networks are presented. Each positive, negative and zero sequence pi-section represents 5 km of cable and the source and transformer impedances are neglected in the calculations.

Maximum fault current

In order to avoid dangerous power equipment voltage rise and to facilitate self-extinction of arcing faults in systems consisting partly of overhead lines, it is important to keep the maximum fault current low. Figure 6.10 shows the maximum earth fault current ($3I_0$) during a solid fault on the busbar in isolated neutral systems of varying total lengths.

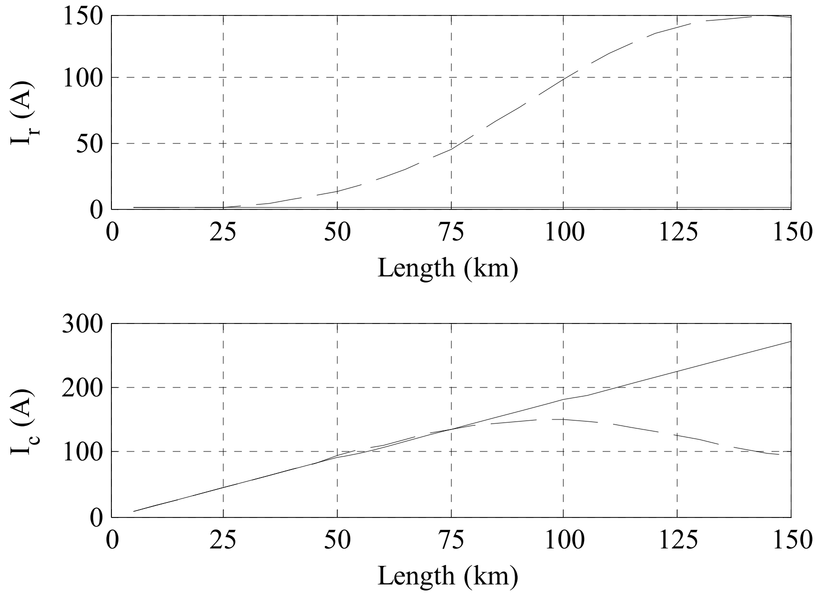

Figure 6.10 Resistive and capacitive earth fault currents in urban system consisting of several short cables (solid line) and rural system consisting of one long cable (dashed line). I_r is practically zero independently of the cable lengths in the urban system.

The results are as expected. The capacitive component of the fault current in the system consisting of several short cables is proportional to the total cable length, and its resistive component is negligible. The earth fault current in the systems consisting of one long cable is not proportional to cable length and consists of a resistive component as well as a capacitive component. While the rural system earth fault current reaches a maximum, the urban system current will continue to increase as the total cable length increase. This current can however be compensated for and the resistive fault current in the rural systems is therefore more critical even if it is lower.

Neutral point displacement voltage

During solid busbar earth faults, the neutral point displacement voltage equals the pre fault phase to earth voltage of the faulted phase, independently of network structure (source and transformer impedance neglected). Voltage drops along the feeder in rural systems will however give an end of line zero sequence voltage that varies depending on the network structure and total cable length. Since the voltage drop has a real and an imaginary part, the zero sequence voltage magnitude can either increase or decrease. Figure 6.11 shows the calculated zero sequence voltage at the end of the feeder in rural systems consisting of one cable of varying length.

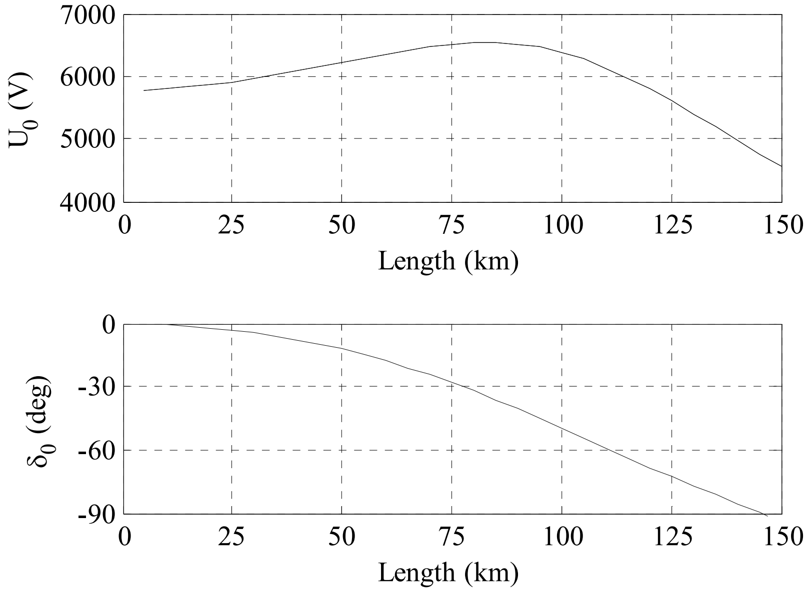

Figure 6.11 Zero-sequence voltages at the end of the feeder during a solid earth fault on the busbar in a rural cable system with a nominal voltage of 10 kV.

6.3 Resonance

As noticed above, the rural system maximum earth fault current is not proportional to cable length. The current peak at 100 km in Figure 6.10, resembles a fundamental frequency resonance peak. Fundamental frequency resonance in conventional overhead line systems requires extremely long feeders and is therefore very seldom of practical interest. The resonance length is determined by the transmission line parameters and since the zero sequence parameters of cables are much different from that of overhead lines, the zero sequence resonance lengths of cables differ from that of overhead lines. The calculations presented above show that provided cable feeders, resonance might influence the earth fault behaviour in systems of practical interest.

The busbar earth fault current contribution of cable feeders with lengths reaching 450 km is shown in Figure 6.12. The current reaches its maximum at approximately 120 km. That is to say, the zero sequence resonance length for cables with parameters according to Table 6.1 is approximately 120 km.

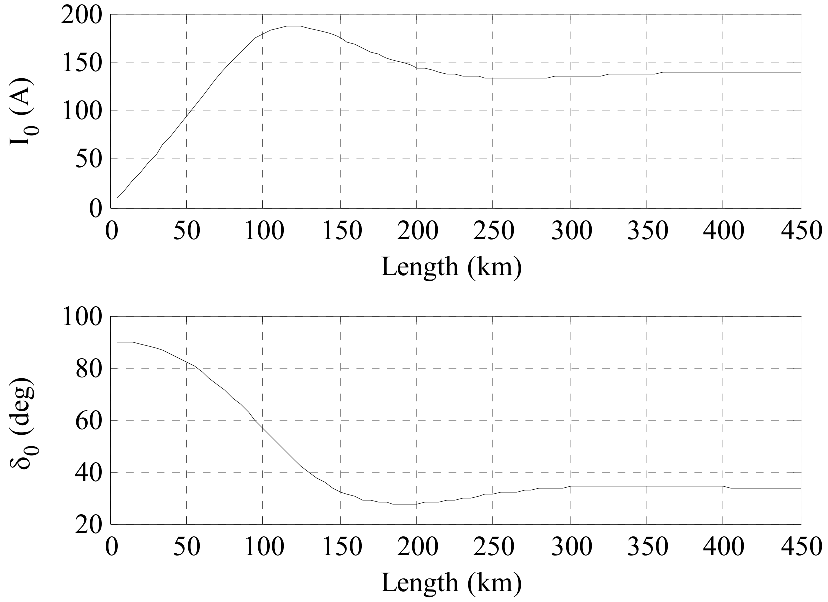

Figure 6.12 Amplitude and phase of busbar earth fault current contribution of cable feeders with lengths vary between 5 and 450 km.

Even if fundamental frequency resonance is not of practical importance in conventional systems, harmonic resonance is. The fundamental frequency resonance in cable feeders can be explained by the same general transmission line theory used to derive harmonic resonance frequencies in conventional systems. While in conventional system resonance calculation, the lengths of the transmission lines are kept constant in order to find the harmonic frequencies, see for example (Faria et al. 2004) (Pignari et al. 2003), in fundamental frequency resonance derivation, the frequency is instead kept constant in order to find the resonance lengths.

General transmission line theory

The widespread *telegrapher's equations* (Claesson et al. 1989) relate voltage and current along a conductor to the series resistance and inductance, and shunt conductance and capacitance of the conductor:

$$\frac{\partial v}{\partial x} = -ri - l\frac{\partial i}{\partial t} \tag{6.8}$$

$$\frac{\partial i}{\partial x} = -gv - c\frac{\partial u}{\partial t} \tag{6.9}$$

Fourier transformation of the telegrapher's expressions, some rearrangement and new notation give the following wave expressions:

$$V(x,f) = V^{+}e^{-\alpha(f)x}e^{-j\beta(f)x} + V^{-}e^{\alpha(f)x}e^{j\beta(f)x} \tag{6.10}$$

$$I(x,f) = I^{+}e^{-\alpha(f)x}e^{-j\beta(f)x} + I^{-}e^{\alpha(f)x}e^{j\beta(f)x} \tag{6.11}$$

$$\gamma(f) = \sqrt{zy} = \sqrt{(r + j\omega l)(g + j\omega c)} = \alpha(f) + j\beta(f) \tag{6.12}$$

The voltage and current along the conductors can both be understood as the combination of two waves, V^+ and I^+ propagating in positive direction and V^- and I^- propagating in negative direction. The wave propagation is controlled by the frequency dependent image attenuation constant in Equation (6.12). The image attenuation constant, γ, consists of a real part, α, as well as an imaginary part, β, both combinations of series impedance and shunt admittance. For each frequency component of V^+, V^-, I^+ and I^-, the magnitude is attenuated by $e^{-\alpha(f)x}$ or $e^{\alpha(f)x}$ and the phase is shifted by β(f)x (Claesson et al. 1989).

The open end transmission line impedance depends on its length as well as the image attenuation constant and the frequency dependent characteristic impedance:

$$Z = \frac{U}{I} = Z_c \frac{e^{\gamma(f)d} + e^{-\gamma(f)d}}{e^{\gamma(f)d} - e^{-\gamma(f)d}} = Z_c \frac{\cosh(\gamma d)}{\sinh(\gamma d)} \tag{6.13}$$

$$Z_c = \sqrt{\frac{(r + j\omega l)}{(g + j\omega c)}} \tag{6.14}$$

Wavelength and resonance in lossless lines

In conventional power system applications, the transmission lines are considered lossless and the image attenuation has no real part. Consequently, there is no wave attenuation and each frequency component of V^+, V^-, I^+ and I^- is phase shifted by an expression determined by conductor inductance and capacitance:

$$\beta(f) = \omega\sqrt{lc} \tag{6.15}$$

During one wavelength, the phase is shifted by 2π:

$$\lambda = \frac{2\pi}{\omega\sqrt{lc}} \tag{6.16}$$

Since there is no attenuation, resonance is first reached when the length of the transmission line equals one fourth of the wavelength:

$$d = \frac{\lambda}{4} = \frac{\pi}{2\omega\sqrt{lc}} \tag{6.17}$$

With overhead line parameters according to Table 6.1, the 50 Hz zero sequence wavelength is approximately 4000 km and resonance is first reached in transmission lines that are approximately 1000 km. Because of the long wavelength and resonance length, the fundamental frequency zero sequence impedance is considered proportional to transmission line length. The same applies to positive and negative sequence impedances.

Resonance in lossy lines

We know that long cables, unlike conventional transmission lines, cannot be considered lossless. In lossy lines, the resonance is attenuated and the derivation of the resonance therefore differs from that in conventional systems. The shunt conductance is however negligible and from Equation (6.10) to (6.14), we get the image attenuation constant, wave propagation, characteristic impedance or the transmission line impedance:

$$\gamma(f)=\sqrt{zy}=\sqrt{(r+\mathrm{j}\omega l)\mathrm{j}\omega c}=\alpha(f)+\mathrm{j}\beta(f) \tag{6.18}$$

$$V(x,s)=V^{+}\mathrm{e}^{-\alpha(f)x}\mathrm{e}^{-\mathrm{j}\beta(f)x}+V^{-}\mathrm{e}^{\alpha(f)x}\mathrm{e}^{\mathrm{j}\beta(f)x} \tag{6.19}$$

$$I(x,f)=I^{+}\mathrm{e}^{-\alpha(f)x}\mathrm{e}^{-\mathrm{j}\beta(f)x}-I^{-}\mathrm{e}^{\alpha(f)x}\mathrm{e}^{\mathrm{j}\beta(f)x} \tag{6.20}$$

$$Z_c=\sqrt{\frac{z}{y}}=\sqrt{\frac{r+\mathrm{j}\omega l}{\mathrm{j}\omega c}} \tag{6.21}$$

$$Z=\frac{U}{I}=Z_c\frac{e^{\gamma(f)d}+e^{-\gamma(f)d}}{e^{\gamma(f)d}-e^{-\gamma(f)d}}=Z_c\frac{cosh(\gamma d)}{sinh(\gamma d)} \tag{6.22}$$

Since both voltage and current are attenuated, resonance will not necessarily occur as the length of the cable reaches one quarter of a wavelength. The resonance length can instead be obtained from the impedance derivative, which gives the minimum transmission line impedance:

$$\frac{dZ}{dd}=0 \tag{6.23}$$

The transmission line length at which resonance is first reached can be found by a quickly converging numerical iteration scheme (Akke 2008):

$$d_1=\frac{\pi}{2\beta} \tag{6.24}$$

$$\theta_k = \arctan\left(\frac{\alpha}{\beta}\tanh(2\alpha d)\right) \tag{6.25}$$

$$d_{k+1} = \frac{\pi - \theta_k}{2\beta} \tag{6.26}$$

Provided parameters according to Table 6.1 the cable feeder zero sequence resonance length converges towards 120 km, which in accordance with the earth fault calculations presented in Figure 6.12. If lossless conditions are assumed the resonance length is instead calculated to 195 km, which is an error that exceeds 60 %. The corresponding lengths calculated with overhead line parameters are 908 km by use of the numerical scheme and 942 km if lossless conditions are assumed and the error is only 4 %.

As the length of the cable increase, the transmission line impedance approaches the frequency dependent characteristic impedance. The 50 Hz characteristic impedance for cables with parameters according to Table 6.1 is 125 Ω. In a 10kV system this corresponds to a solid busbar earth fault current that is approximately 140 A, which is in accordance with the earth fault calculations presented in Figure 6.12.

Variable frequencies

Resonance length and characteristic impedance of lossy lines are frequency dependent. The numerical iteration scheme above can be used to calculate the zero sequence resonance length for any frequencies. The calculated resonance lengths for harmonics frequencies between 10 and 10 000 Hz are shown in Figure 6.13.

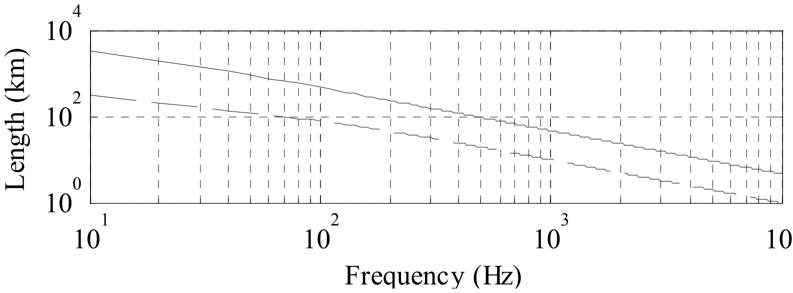

Figure 6.13 Calculated cable (dashed) and overhead line (solid) resonance lengths for harmonic frequencies.

Harmonics, like fundamental frequency, require a shorter cable feeder than overhead line, to reach resonance. Cables will therefore exhibit resonance for a larger number of frequencies, compared to overhead lines of equal length. As an example 300 Hz resonance can be reached in cables of lengths between 20 and 30 km while corresponding overhead line resonance length is approximately 200 km.

6.4 Influence of fault location

Now, we instead consider an earth fault at the end of a cable. The sequence networks in Figure 6.14 represents an end of line earth fault in an urban system. The positive and negative series impedances of the faulted line are part of the equivalent impedance of the system, but since the length of the feeders is limited, the series impedances are negligible. The equivalent impedance is solely capacitive and similar to that during an earth fault on the busbar; the location of the fault does not influence the earth fault behaviour of the conventional urban cable system.

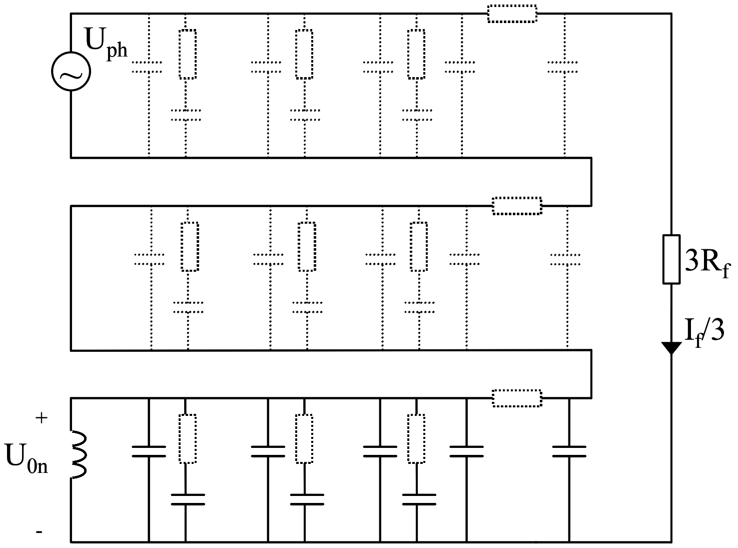

Figure 6.14 Sequence networks representing an end of line fault in an urban system. The series impedance is negligible and does not influence the earth fault behaviour.

Figure 6.15 represents an end of line earth fault in a rural system. In addition to the equivalent zero sequence impedance, the positive and negative impedances influence the fault behaviour. The size of the equivalent sequence impedances varies depending on where the fault is located and consequently, the equivalent impendence and the earth fault current depend on fault location.

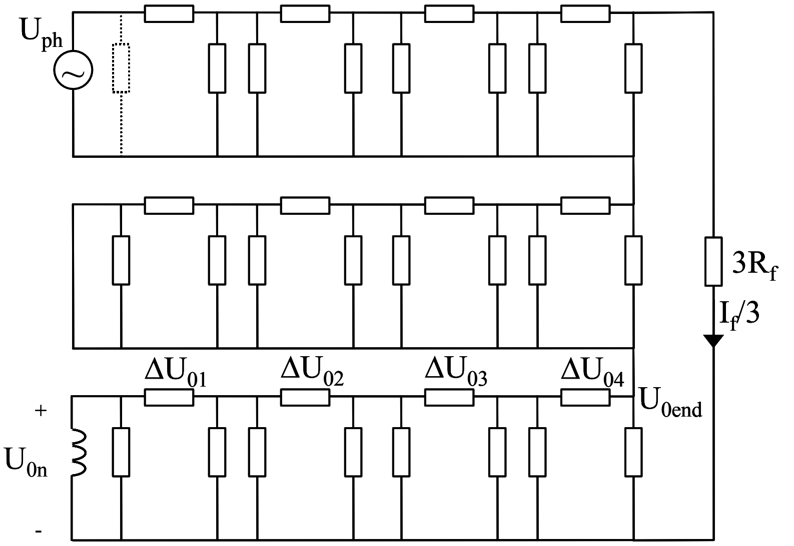

Figure 6.15 Sequence networks representing an end of line fault in a rural system with non-negligible series impedance.

Since there are voltage drops across the non-negligible series impedances of the faulted feeder, the amplitude and the phase of the neutral point displacement voltage (U_{0n}) are different from that of the zero sequence voltage at the fault location (U_{0end}). The voltage drops depend on the size and phase of the zero sequence current as well as the size and phase of the equivalent zero sequence series impedance and hence depend on the network structure and the location of the fault. In addition, the voltage drops across the equivalent positive and negative impedances, influence the zero sequence voltage at the fault location so that it differs from the phase voltage, even if the fault impedance is negligible.

Petersen coil tuning

In rural systems, the location of the fault influences the neutral point displacement voltage as well as the earth fault current. These in turn, influence important aspects of Petersen coil tuning. The neutral point displacement voltage determines the inductive current generated by the Petersen coil and the earth fault current determines the size of the required compensation current. Since the inductive current is generated at the busbar, and the capacitive current that shall be compensated for is generated continuously along the feeder, they do not respond similarly to variations in fault location and consequently, the coil cannot be tuned to compensate the capacitive fault current to the same degree, independently of fault location. If the Petersen coils are tuned for busbar faults, faults on other locations will be compensated to other degrees than the intended.

Unexpected neutral point displacement voltage and its effects on the compensation current are sometimes observed in real systems and field tests. As an example, a Sydkraft (now E.ON) report on the Stenestad cable system field tests, relates unexpected compensation currents to neutral point displacement voltage much different than expected (Messing 2001). In the report, the unexpected neutral point displacement voltage is however supposed to have other reasons than the voltage drop along the feeder that is presented above.

Calculated maximum fault current

We consider the maximum earth fault current as a worst-case scenario. It is therefore interesting to find for which fault location the maximum fault current is reached. Figure 6.16 shows the calculated resistive and capacitive earth fault current during a busbar fault and an end of line fault, in resonance earthed rural systems tuned for faults on the busbar. The Petersen coil inductance is 105 % of the resonance value and its resistive losses are 2 %. This is in accordance with available manufacturer data as well as models used in previous studies (Akke 2006) (Elforsk 2006). The phase of the current is referred to the neutral point displacement voltage.

The calculations show that the fault current during an end of line fault is smaller than the fault current during a busbar fault. This is because the positive and negative impedance contribute to the equivalent impedance, which limits the earth fault current. The resonant earthing decreases the earth fault current but since the Petersen coils cannot be tuned to compensate to the same degree independently of fault location, the influence of the earthing will vary depending on fault location.

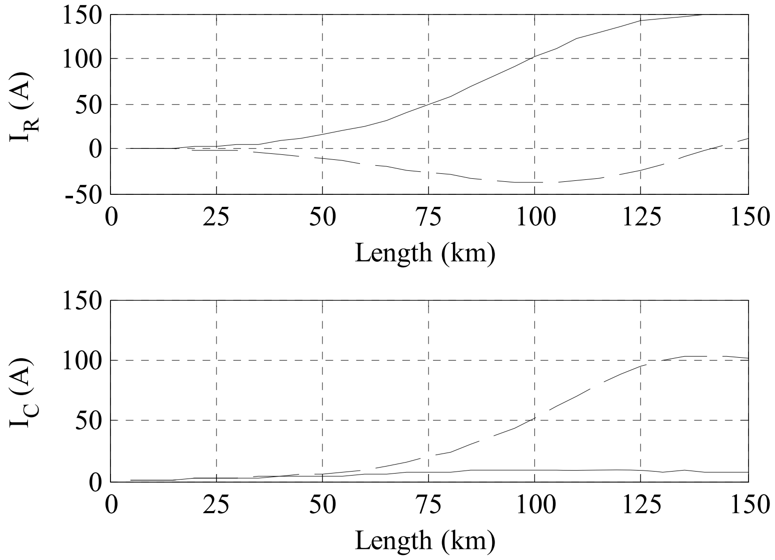

Figure 6.16 Fault currents at the fault location during solid busbar earth fault (solid) and solid end of line earth fault (dashed) in a traditionally resonance earthed rural cable system.

Figure 6.17 shows calculated currents for an earth fault at the end of the feeder in isolated neutral and resonance earthed systems tuned for faults on the busbar. The Petersen coil does not compensate for the entire capacitive current but the current amplitude is decreased compared to that in an isolated neutral system. It is also smaller than the almost solely resistive compensated busbar earth fault current. Even though the calculations show that the earth fault current is larger for faults on the busbar than for faults at the end of the cable feeder, we cannot conclude that a fault on the busbar gives maximum earth fault current.

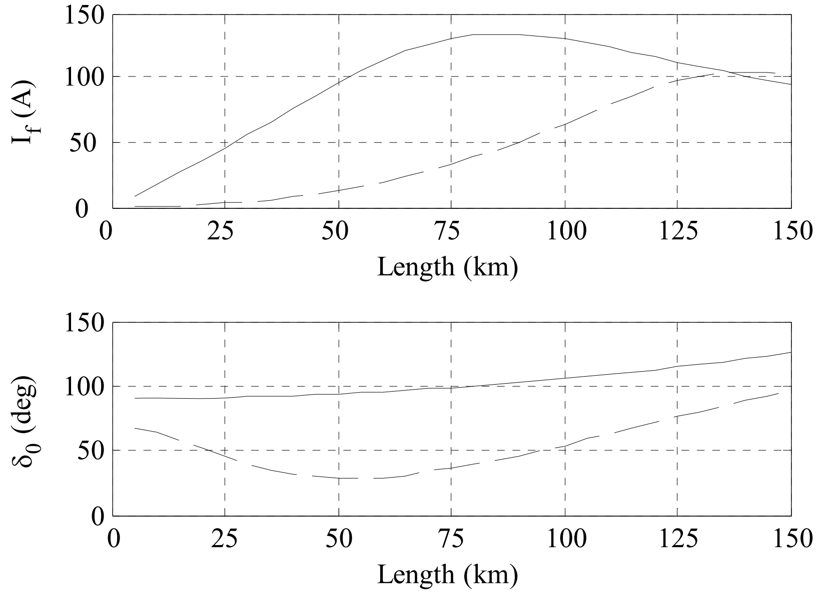

Figure 6.17 Earth fault current calculated for faults at the end of the feeder in isolated systems (solid) and resonance earthed systems (dashed).

Figure 6.18 shows how the earth fault currents in resonance earthed systems with cable lengths of 50, 100 and 150 km depend on the fault location. As expected, the fault location is of little influence to the earth fault current if the length of the cable is limited. This is because the series impedance is relatively small and does not considerably influence the earth fault behaviour of the system.

For long cables, the fault location influences the magnitude as well as the phase of the earth fault current. The amplitude of the maximum busbar fault current does not differ considerable from the amplitude of the maximum earth fault current of the system. The fault current generated during an earth fault at the busbar is to a larger degree in phase with the neutral point voltage, than the fault current generated during an earth fault at the end of the feeder.

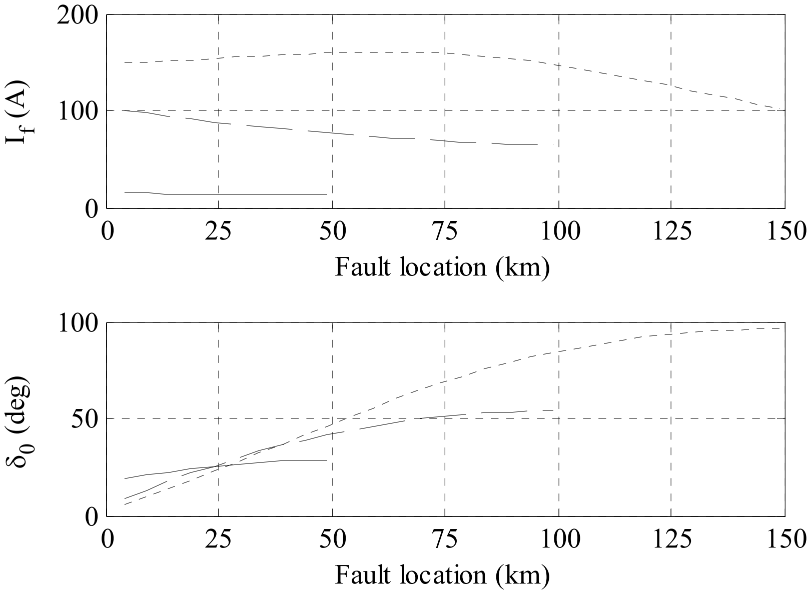

Figure 6.18 Earth fault current in a 50 km (solid), a 100 km (dashed) and a 150 km (dotted) cable system. The horizontal axis shows the distance between the busbar and the fault location.

Calculated neutral point displacement voltage

As explained above, the fault location influences the zero sequence voltage in the system. If the solid earth fault is located on the busbar, the neutral point displacement voltage equals the pre fault phase to earth voltage. This is not necessary the case if the fault is located at the end of the cable feeder or anywhere else in the system.

Figure 6.19 shows the neutral point displacement voltage and the zero sequence voltage at the fault location during a solid end of line earth fault in a resonance earthed system with one cable feeder of varying length. As expected, the voltages decrease as the length of the cable increase. The decrease of the zero sequence voltage at the fault location is due to voltage drops across the positive and negative sequence impedance, while the difference between the zero sequence voltage at the fault location and the neutral point displacement depends on the voltage drop across the zero sequence impedance.

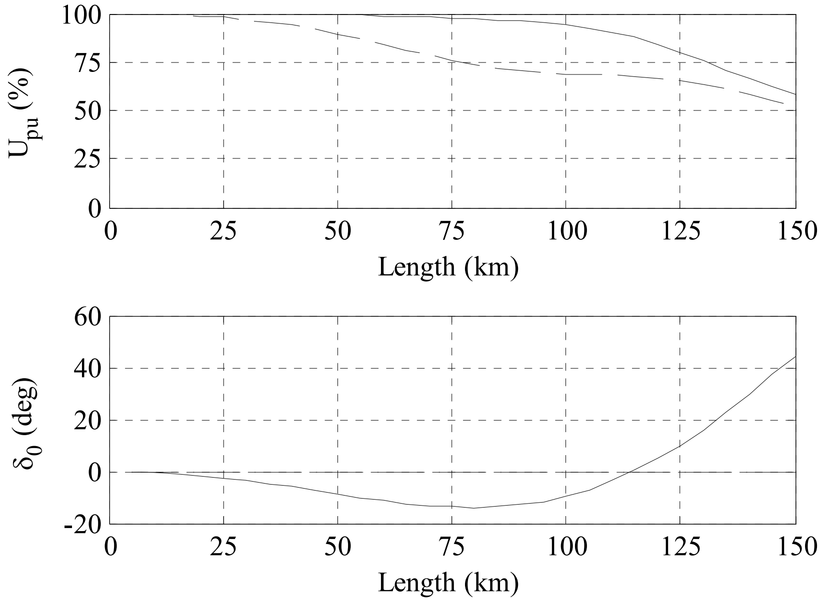

Figure 6.19 Neutral point displacement voltage (dashed) and zero sequence voltage at fault location (solid) during an end of line fault in a resonance earthed system. The phase is related to the neutral point displacement voltage.

6.5 High-impedance fault detection

According to the Swedish high voltage standards, earth faults with fault resistance up to 3 kΩ (5 kΩ) must be detected in the electrical distribution systems (ELSÄK-FS 2008:1). In conventional systems with negligible series impedance, the zero sequence voltage is equal all over the system and zero sequence voltage measurements are not sufficient to attain selective earth fault detection. Instead, the neutral point displacement voltage is typically used for detection, and to trigger a selective method, such as directional residual (zero sequence) current measurements (Griffel et al. 1997) (Roberts et al. 2001).

The directional residual current relays measure the resistive part of the zero sequence current. The resistive current component is always directed from the healthy feeders and the busbar towards the fault location and can thereby be used for selective fault detection. The direction of the reactive current might vary depending on the tuning degree of the system, and ought therefore not to be used for selective fault detection by use of residual current measurements.

The sequence networks in Figure 6.20 represents an earth fault on one of the feeders in a two-feeder resonance earthed network. A neutral point resistor is connected in parallel with the Petersen coil. The resistive current I_{01R} is directed from the busbar towards the faulted feeder. The resistive current is the combination of I_{0nR} which is the current generated in the neutral point resistance and I_{02R} which is the resistive component of the current that flow through the equivalent impedance of the healthy line. In conventional systems consisting of overhead lines and short cables, the equivalent impedance of the healthy feeders is solely capacitive and there is no resistive current component flowing from the healthy feeders towards the fault location. The resistive current measured by the residual current relays thereby equals the resistive current generated by the earthing equipment.

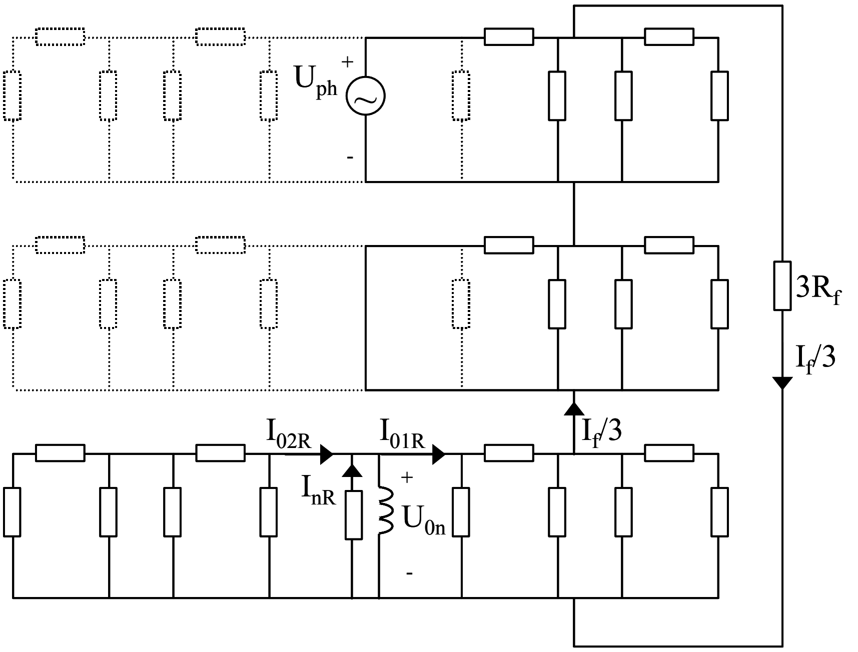

Figure 6.20 Sequence network representing an earth fault on one feeder in a two-feeder network. $I_{01R}= I_{nR} + I_{02R}$.

Damping

We have seen that the network structure and the fault location influence the equivalent impedance and the solid earth fault behaviour of electrical distribution systems, but the network structure is also of great importance to the system behaviour during high-impedance faults. Figure 6.21 shows the equivalent circuit of a distribution system with an earth fault on the busbar. The resistance and capacitance in the figure is the parallel impedance equivalents of the total cable impedance.

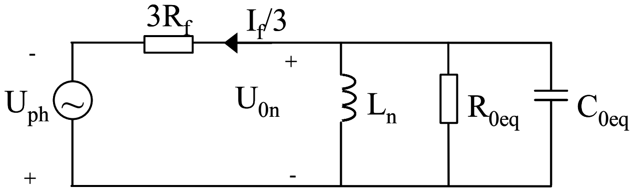

Figure 6.21 Equivalent circuit during an earth fault on the busbar in a resonance earthed rural system.

The neutral point displacement voltage depends on how large the equivalent zero sequence impedance of the system is in relation to the fault impedance:

$$U_{0n} = U_{ph} \frac{Z_{0eq}}{3R_f + Z_{0eq}} \tag{6.27}$$

In resonance earthed systems, the inductance of the Petersen coil is dimensioned so that the inductive reactance equals the capacitive reactance of the feeders. The resulting reactance is thereby very large. In urban systems, there are no resistive losses, and the equivalent zero sequence impedance equals the large resulting reactance. The neutral point displacement voltage will therefore reach a significant magnitude also during high-impedance faults.

The resistive component of the zero sequence impedance in rural cable systems decreases the equivalent zero sequence impedance and damps the resonance. Even if the inductance and capacitance are tuned to resonance, the equivalent impedance will be limited by the value of the parallel equivalent of the zero sequence resistance, which decreases as the length of the cable increase. For long cables, the fault impedance might be very large compared to the zero sequence impedance and the neutral displacement voltage thereby small:

$$U_{0n} = U_{ph} \frac{R_{0eq}}{3R_f + R_{0eq}} \tag{6.28}$$

Figure 6.22 shows the neutral point displacement voltage during 5 kΩ end of line earth faults in rural systems consisting of one and two cable feeders. Since the equivalent parallel resistance decreases as the length of the cable increases, the fraction of the pre fault voltage that is applied across it, and by that the neutral point voltage, will decrease.

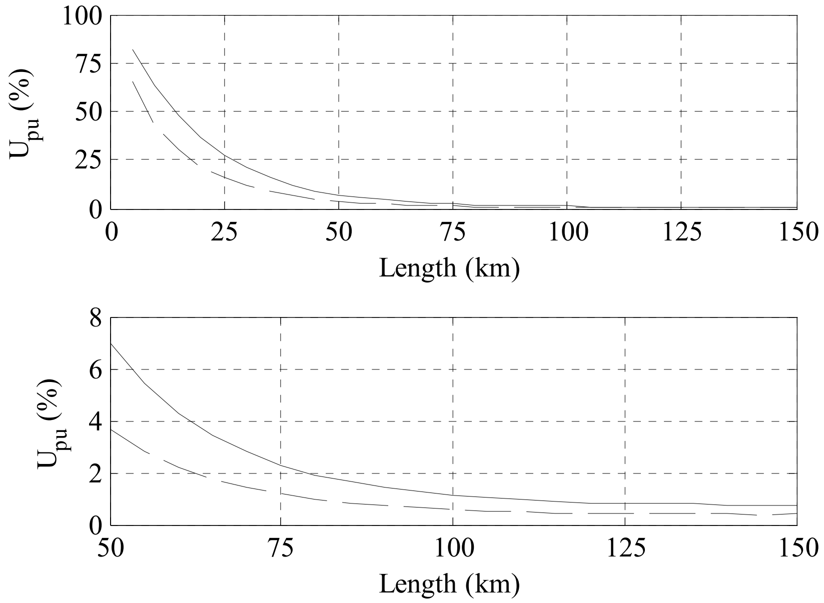

Figure 6.22 Neutral point displacement voltage during a 5 kΩ end of line earth faults in rural systems consisting of one (solid) or two (dashed) cables. The voltage is related to the pre fault phase voltage. The cable feeder lengths vary between 5 and 150 km (upper), and 50 and 150 km (lower).

If systems with long cables are analysed according to conventional practice, all resistive losses will be neglected and the expected neutral point displacement voltage and the resistive current generated in the neutral point resistance considerable higher than the actual values. If the relay thresholds are set according to the expected values, the fault might not be detected. This phenomenon was observed during the E.ON Stenestad field tests, mentioned above (Messing 2001) and has also been documented by Vattenfall (Vikman 2005) and treated in (Elforsk 2006).

Even if a correct analysis is carried out, it might be very difficult to find relay thresholds that allow sensitive earth fault detection in systems where resistive damping influences the neutral point displacement voltage. Sensitive voltage relays can reliable detect zero sequence voltages down to approximately 3 % of the phase voltage (Lindahl et al. 1991). From Figure 6.22 we see that if the relays are set in accordance with the conventional 3 % minimum threshold, 5 kΩ earth faults are not necessarily detected in resonant earthed neutral systems consisting of long cable feeders.

Swedish high voltage regulations state 5 kΩ earth fault resistance as a limit for required detection, but it is sometimes desirable to detect faults with higher impedance. Figure 6.23 shows calculated neutral point displacement voltage during a high-impedance earth fault in a resonance earthed system consisting of two 50 km cable feeders. The fault impedance is varied between 5 and 25 kΩ. If the voltage relays are set in accordance with conventional sensitive threshold of 3%, faults with impedance that exceeds approximately 6 kΩ cannot be detected

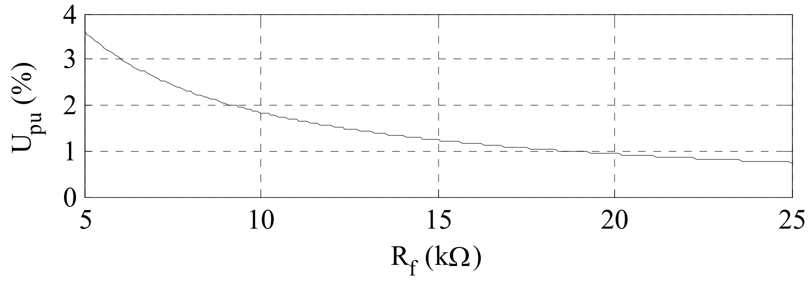

Figure 6.23 Neutral point displacement voltage during a high-impedance earth fault in a resonance earthed system consisting of two 50 km cable feeders. The neutral point voltage is related to the pre fault phase voltage.

6.6 Multiple feeders

Sequence networks analysis can be used to analyse the earth fault behaviour of any distribution system as long as the equivalent sequence impedance of the systems either is known or can be calculated.

During a busbar fault, the equivalent impedance of the system equals the zero sequence impedance as seen from the busbar towards the zero sequence zero potential bus. The zero sequence network of a system with two long cable feeders consists of two parallel lines of series connected pi-sections. If the system consists of two equally long cables, the equivalent impedance is therefore half of that of a single radial system and consequently, the total earth fault current is twice that in a single radial system. Analogously, the zero sequence network for n long cables consists of n parallel lines of series connected pi-sections and the total earth fault current is n times the current in a single radial system. Figure 6.24 shows the maximum busbar earth fault current in a resonance earthed system with several feeders.

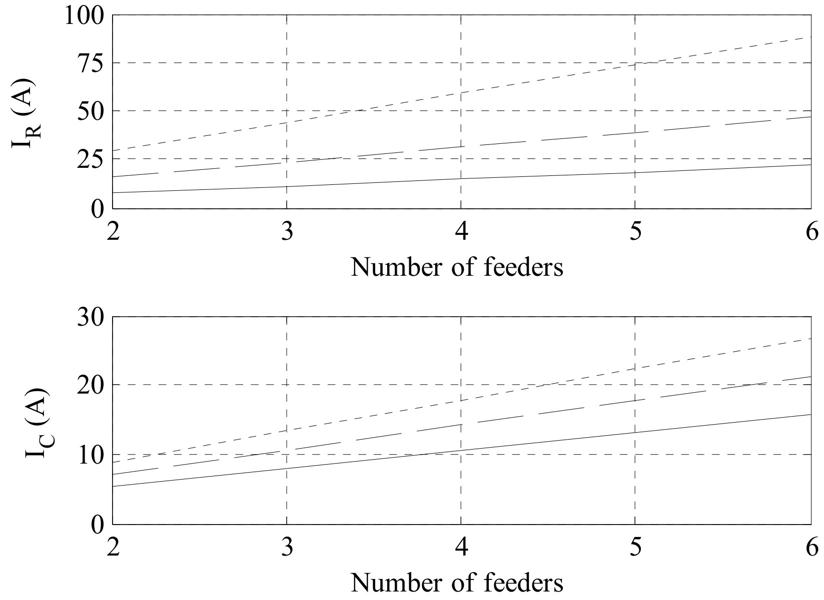

Figure 6.24 Maximum busbar earth fault current in resonance earthed systems with multiple feeders, each 30 (solid), 40 (dashed) or 50 km (dotted). The inductance of the Petersen coil is 105 % of the resonance value.

As expected, the magnitude of current is proportional to the number of feeders while the phase is not affected by the number of feeders. Since the equivalent impedance of cable feeders is nonlinear, the amplitude of the current is however not proportional to cable length. The difference between the fault current in 3x40 km and a 3x50 km systems is larger than the difference between the earth fault current in 3x30 km and 3x40 km systems.

The positive and negative sequence networks representing a system with n long cable feeders do also consist of n parallel lines of series connected pi-sections. The equivalent positive and negative impedances are parts of the equivalent system impedance if the fault does not occur on the busbar but anywhere on a cable feeder. During a fault on a feeder, the sequence impedances of the faulted line are not connected in parallel with the impedance of the healthy lines and the fault current is not exactly, but close to, proportional to the number of feeders.

The number of feeders also influences the possibility of high-impedance earth fault detection. Figure 6.25 shows the calculated neutral point displacement voltage during a 5 kΩ busbar fault in the resonance earthed systems presented above. If an additional feeder is connected to a system, the equivalent impedance decreases while the fault impedance remains the same. The neutral point displacement voltage is therefore reduced. The systems will show similar behaviour during an earth fault on a feeder.

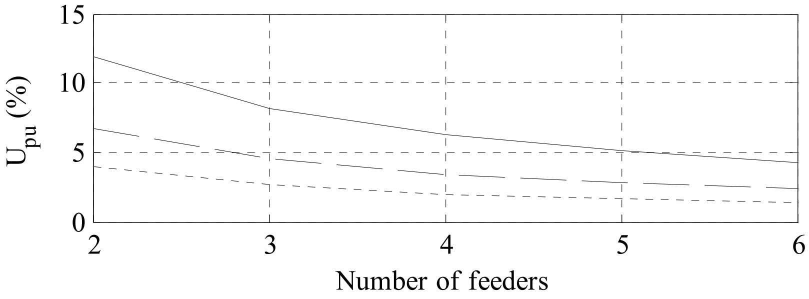

Figure 6.25 Neutral point displacement voltage during a 5 kΩ busbar fault in the resonance earthed systems with multiple feeders, each 30 (solid), 40 (dashed) or 50 km (dotted).

6.7 Branched cable feeders

It is not likely that the new rural cable systems will consist of radial feeders as long as 100 or 150 km. There are however considerably shorter cable feeders whose series impedance might influence the system earth fault behaviour.

Now we consider a branched system as that shown in Figure 6.26. The earth fault behaviour of this system is neither similar to that in a system with several short cables nor to that of a system with one single long radial.

As mentioned above, an urban network with several short cables can be seen as a parallel connection and the relation between the series impedance and the capacitive shunt impedance is therefore equal to that of one short cable. A strictly radial feeder can be seen as series connection of n short cables and the ratio between the series impedance and the capacitive shunt impedance is therefore in the order of n^2 times that of that of the short cables.

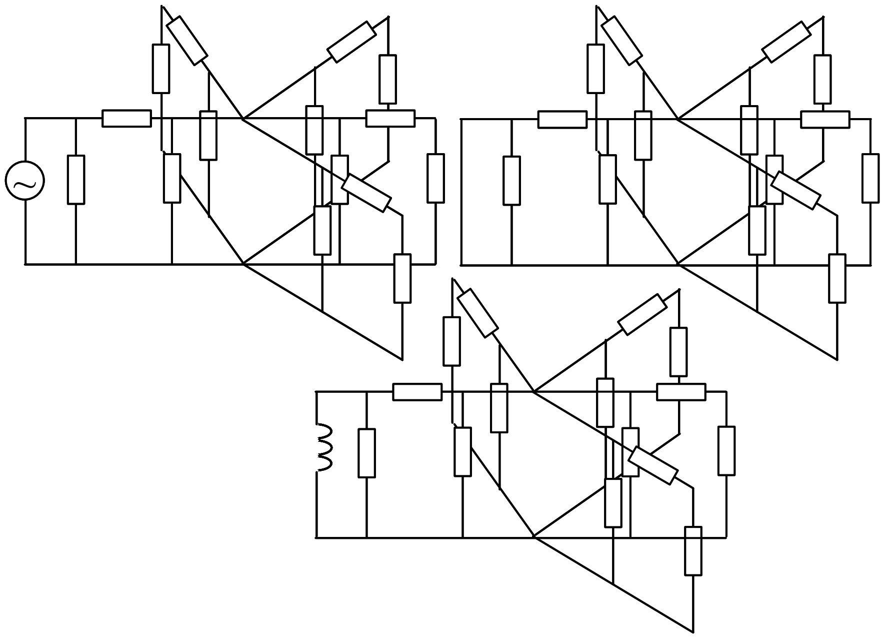

Figure 6.26 Positive, negative and zero sequence network equivalents of a branched resonance earthed cable system

Figure 6.27.shows the network equivalent of a busbar earth fault in the branched system in Figure 6.26 (provided all pi-sections represent the same cable length) and Figure 6.28 shows the same connection with additional simplifications.

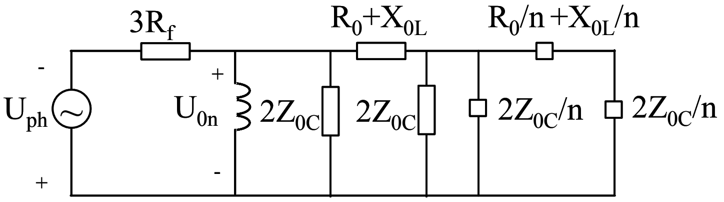

Figure 6.27 Simplified sequence network equivalent of an earth fault on the busbar in a branched resonance earthed system with n branches.

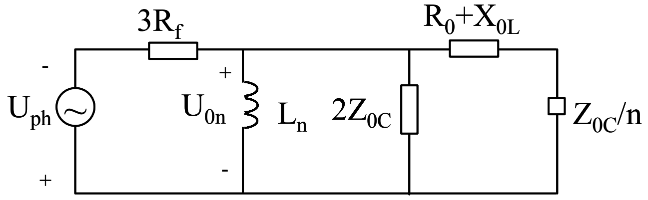

Figure 6.28 Additionally simplified sequence network equivalent of an earth fault on the busbar in a branched resonance earthed system with n branches.

The relation between the equivalent sequence series impedance and the sequence capacitive shunt impedance of the branched system will be in the order of n times that of a short cable:

$$Z_{0eq} = R_0 + j\omega L_0 + Z_{0eq(n)} \tag{6.29}$$

$$Z_{0eq} = R_0 + j\omega L_0 + \frac{1}{n}\cdot\left(R_0 + j\omega L_0 + \frac{2}{j\omega C_0}\right) // \frac{1}{n}\cdot\frac{2}{j\omega C_0} \tag{6.30}$$

$$Z_{0eq} \approx R_0 + j\omega L_0 + \frac{1}{n}\cdot\frac{2}{j\omega C_0} \tag{6.31}$$

The analysis indicates that the earth fault behaviour of traditionally earthed systems with branched feeders are less severe than that of systems that consist of few long, strictly radial, feeders but more severe than that of systems that consist of several short feeders. The branched systems have many similarities with real systems and are thereby possibly of more practical interest than the behaviour of systems with extremely long strictly radial feeders. Simulated earth fault behaviour in branched systems is presented in Chapter 9.

6.8 Load influence

The above calculations are all based on no-load condition. It might however be of interest to analyse how a symmetrical load influences the earth fault behaviour. In sequence network analysis, symmetric loads connected to the LV network are represented by positive and negative sequence parameters. Figure 6.29 shows the sequence network representation of a busbar earth fault in a resonance earthed rural system with symmetric loads. The symmetric constant impedance loads are represented by the phase to earth impedances marked grey in the positive and negative sequence networks. The positive and negative sequence networks do not affect the system behaviour during a busbar fault and the earth fault behaviour is therefore not influenced by the symmetric loads.

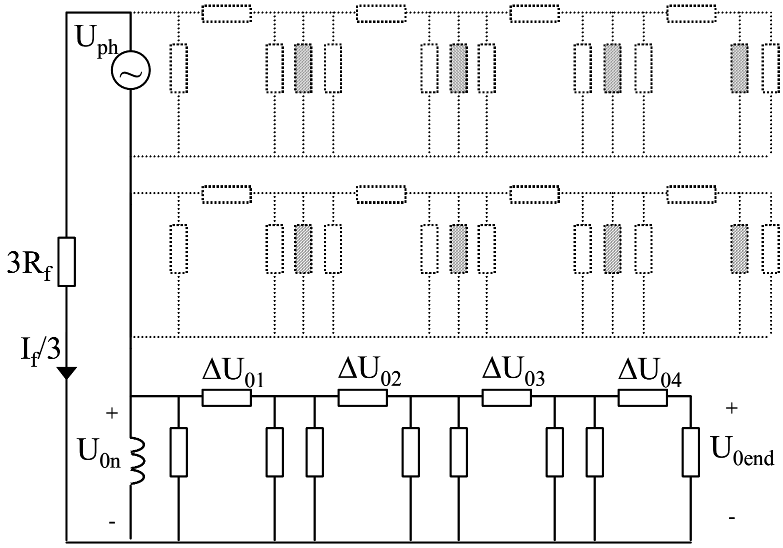

Figure 6.29 Busbar earth fault in a resonance earthed rural system with symmetric constant impedance loads. The symmetric loads are represented by the phase to earth impedances marked grey in the positive and negative sequence networks.

Figure 6.30 shows the sequence network representation of an earth fault at the end of the feeder. Here, the positive and negative sequence impedance is part of the equivalent impedance of the system and consequently the symmetrical loads influence the earth fault behaviour. The level of influence depends on the size and phase of the load impedance, the neutral point equipment, size and structure of the system, and in particular the fault impedance.

A resistive symmetric load will decrease the equivalent impedance of the positive and negative sequence network and by that increase the positive sequence current and the voltage drop across the positive sequence series impedances. If the voltage drop across the positive sequence series impedance increases, the zero sequence voltage at the fault location decreases and as a result, the earth fault current is lower than under no load condition.

If the fault impedance is large compared to the equivalent positive sequence impedance, the symmetrical load will not considerably influence the earth fault behaviour of the system.

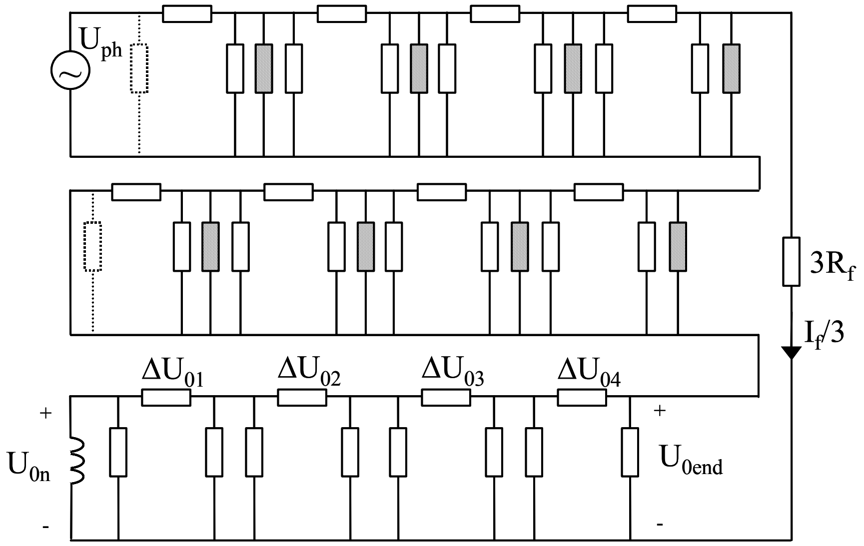

Figure 6.30 End of line earth fault in a resonance earthed rural system with symmetric load. The symmetric loads are represented by the phase to earth impedances marked grey in the positive and negative sequence networks.

Chapter 7

Distributed compensation

The calculations presented in the previous chapters show that the zero sequence series impedance influences the earth fault behaviour in systems with long cable feeders so that the equivalent impedance of the feeder has a resistive as well as a reactive part. The resistance damps the resonance in conventionally resonance earthed systems, and by that increases the low-impedance earth fault current and decreases the high-impedance fault neutral point voltage. Since the damping can have severe consequences to the safety of the systems, it is necessary to somehow decrease the influence of the series impedance on the earth fault behaviour in systems that consist of long cables.

The influence of the zero sequence series impedance will decrease if the size of the shunt impedance is increased. The size of the cable feeder zero sequence shunt impedance can be increased by using local Petersen coils. Earthing with local Petersen coils is often referred to as distributed compensation. Distributed compensation was briefly discussed in Chapter 4, but will be further studied in this chapter. Distributed compensation is not widely used and the number of available publications on the subject is limited. One relatively early publication concerns distributed compensation in Finish overhead line systems (Nikander et al. 1997). In this paper, it is found that distributed compensation has several advantages compared to conventional resonance earthing. It decreases the hazardous voltages and facilitates sensitive earth fault detection. Since the paper concerns overhead line systems, which have a much weaker capacitive connection to earth compared to cable systems, only feeders with lengths close to 100 km is considered for distributed compensation.

E.ON has documented some of their work regarding the introduction of local compensation. One of the E.ON reports describes difficulties in early field tests involving distributed compensation (Messing 2001). A large part of these difficulties now seems to have been solved. A later E.ON report that mainly concerns field test of the compensation equipment concludes that the measurements are essentially in accordance with equipment data (Akke 2006). The observed improvements between 2001 and 2006 can be seen as signs of a maturing industry. It has taken a couple of years to develop equipment that works as expected.

In a more general report issued by E.ON, (Messing 2005) it is stated that conventional earthing is not always sufficient to ensure safety in distribution systems consisting of long cables. It is concluded that distributed compensation might decrease low-impedance fault currents and facilitate high-impedance fault detection. This is on the condition that the distributed compensation is implemented correctly and the local coils are associated with relatively small resistive losses. The report is mainly based on simulations and the circuit analysis presented in the report is limited.

During 2006, an Elforsk cable system project was carried out aiming to study the influence of distributed compensation on systems consisting of long cables (Elforsk 2006). EMTDC simulations were used to compare distributed compensation to conventional resonance earthing. The results indicate that distributed compensation will decrease low-impedance earth fault current and increase high-impedance neutral point displacement voltage. The report says little to explain the presented results.

7.1 Network representation

The local Petersen coils of systems with distributed compensation are located in MV to LV transformers along the transmission lines. For the influence of the series impedance to be as small as possible, the equivalent zero sequence shunt impedance shall be as large as possible. Maximum shunt impedance is reached if each local coil is dimensioned to compensate for the equivalent capacitance of the cable section - typically a few km - between two adjacent local coils:

$$X_{shunt} = \frac{\omega 3L_{local} \cdot \dfrac{1}{\omega C_{0xkm}}}{\dfrac{1}{\omega C_{0xkm}} - \omega 3L_{local}} \qquad (7.1)$$

$$3L_{local} \rightarrow \frac{1}{\omega^2 C_{0xkm}} \Rightarrow X_{shunt} \rightarrow \infty \qquad (7.2)$$

Figure 7.1 shows the sequence network representation of a rural system with distributed compensation. Since the transmission line is modelled by pi-sections, the modelled capacitance is lumped and if the local Petersen coils are dimensioned for resonance, the modelled shunt impedance is infinite.

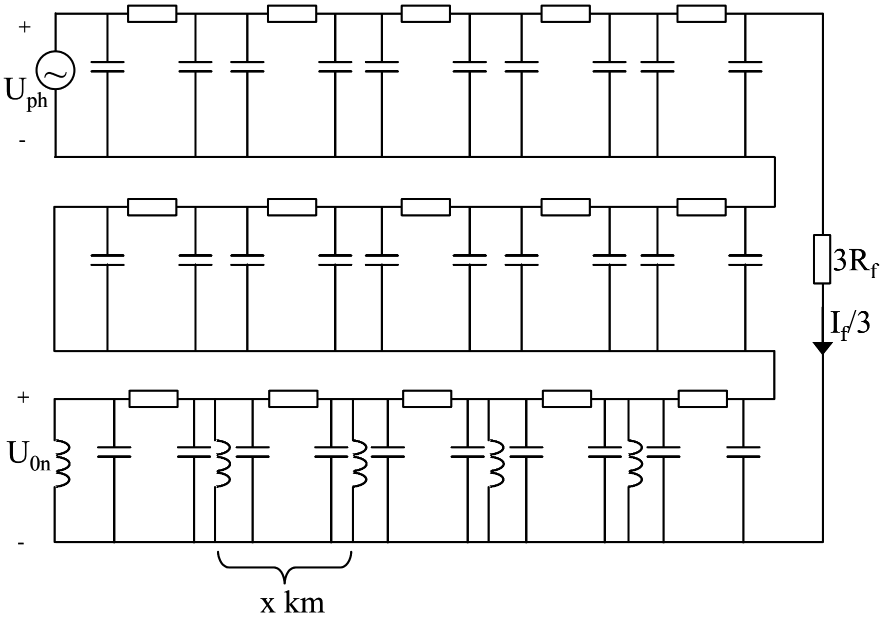

Figure 7.1 Earth fault at the end of the feeder in a locally compensated rural system consisting of one long feeder. The distance between the local Petersen coils is x km.

In reality, the capacitive connection to earth is distributed and the shunt impedance is therefore finite. It decreases as the distance between the compensation coils increases. Consequently, the influence of the series impedance, the resistive part of the equivalent impedance and the resistive earth fault component increase as the distance between the coils increases.

In addition, the Petersen coils are associated with resistive losses that contribute to the resistive part of the equivalent zero sequence impedance and the earth fault current. The resistive current are proportional to the coil size.

If the local coils are dimensioned for resonance, their number, or size, is proportional to cable length and the total resistive Petersen coil losses are thereby proportional to total cable length.

Figure 7.2 shows how the magnitude of the maximum earth fault current depends on the distance between the local coils.

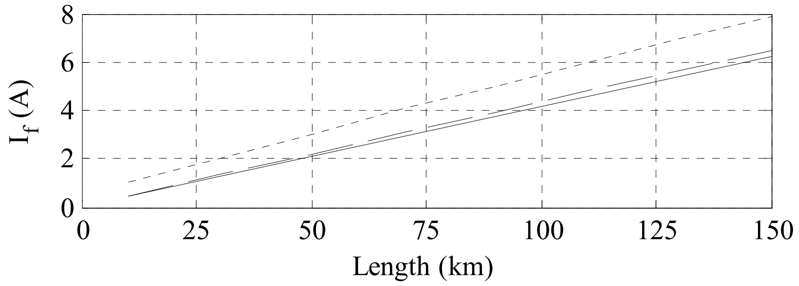

Figure 7.2 Maximum earth fault current in locally compensated systems. The distance between the compensation coils is 5 km (solid line), 10 km (dashed) or 20 km (dotted). The losses in the Petersen coils are approximately 2.5 %.

As long as the distance between the coils are 5 or 10 km almost all the current is due to the coil losses and do therefore not differ depending on the distance between the coils. If the distance between the coils is instead 20 km, the series impedance of the feeder sections contributes to the equivalent impedance, and the resistive earth fault current increases. If the distance between the coils is short, the zero sequence current is small, and the voltage drops across the zero sequence series impedance therefore limited. Consequently, the zero sequence voltage will be similar all over the system.

The fault location in Figure 7.1 is on the cable feeder end. The positive and the negative sequence series impedance are therefore part of the equivalent impedance of the system.

Influence of fault location

Figure 7.3 shows the sequence network equivalent of an earth fault somewhere on a feeder in a locally compensated system. If the distance between the compensation coils is limited, the influence of the zero sequence series impedance is negligible and the resulting zero sequence impedance thereby large and independent of fault location. The positive and negative sequence networks are not influenced by the local compensation and their series impedances are not necessarily negligible compared to the shunt impedances.

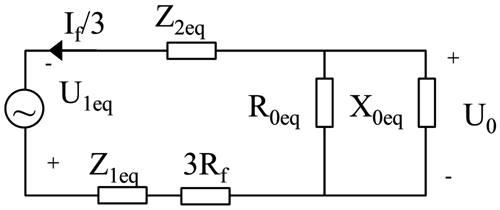

Figure 7.3 Equivalent circuit of earth fault in locally compensated system

The equivalent positive sequence voltage source and the positive and negative sequence impedance vary depending on the fault location. However, the zero sequence impedance is large, and the earth fault current therefore small and the influence of the positive and negative impedance limited, regardless of fault location. The size of equivalent positive sequence voltage source depends on the voltage drops across the positive series impedances. Since the positive sequence capacitance is relatively large in systems consisting of long cable feeders, the capacitive positive sequence current might be considerable and thereby influence the positive sequence voltage along the cable in normal operation as well as under faulted conditions.

In systems with distributed compensation, the variations in zero sequence voltage will have the same effect on the local compensation coils as on the capacitive current between phase and earth. The inductive current generated in the local Petersen coils will therefore compensate the capacitive current to the same degree, regardless of the fault location.

Sensitive earth fault detection

The high-impedance earth fault neutral point displacement voltage is central to earth fault detection in resonance earthed systems. In locally compensated resonance earthed systems the positive and the negative series impedances are small compared to the zero sequence impedance, and their influence on the zero sequence voltage is therefore negligible. The zero sequence voltage does thereby only depend on the equivalent positive sequence voltage source and the relation between the fault impedance and the zero sequence impedance:

$$U_0 = U_{1eq} \cdot \frac{Z_{0eq}}{Z_{0eq} + 3R_f} \tag{7.3}$$

If the distance between the compensation coils is small, the series impedance is negligible, and the resistive part of the zero sequence voltage is only due to Petersen coil losses. This means that the equivalent parallel series resistance is large and the zero sequence voltage is kept relatively high, even during high-impedance faults. If the earth fault current is small, the voltage drop across the zero sequence series impedance is small and the neutral point displacement voltage do not differ considerable from the zero sequence voltage at the fault location, regardless of fault location.

Figure 7.4 show the neutral point displacement voltage during a 5 kΩ fault in conventionally resonance earthed systems and systems with distributed compensation. The systems each consist of one long feeder and the fault is located at the end of this feeder.

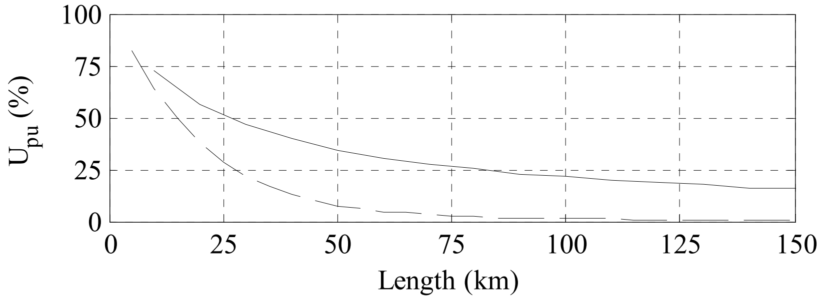

Figure 7.4 Neutral point displacement voltage during a 5 kΩ earth fault in systems with distributed compensation (solid line) and conventionally resonance earthed systems (dashed line).

The neutral point displacement voltage is considerable higher in the locally compensated systems than in the systems with conventional earthing. Providing a maximum cable length of 150 km and a distance of 5 km between the local Petersen coils, the neutral point displacement voltage does not go below 15 % of the pre fault phase to earth voltage.

7.2 Local Petersen coil rating

Distributed compensation has already been introduced in Swedish electrical distribution systems. ABB, Hexaformer and Transformer all provide transformers and Petersen coils that are suitable for local compensation (ERA 2007). At least one of these manufacturers provides local compensation coils that are dimensioned to compensate for the capacitive earth fault current of 5 km cable (Transfix 2005). Since the zero sequence capacitance of 10 kV underground cables (95 mm^2 XLPE cables with circular conductors) is approximately 0.33 μF per km, the total capacitive impedance of 5 km cable is 1930 Ω:

$$X_{C0} = \frac{1}{\omega \cdot 5 \cdot 0.33 \cdot 10^{-6}} = 1930\Omega \tag{7.4}$$

The impedance corresponds to local compensation coils of 2 H each.

$$L = \frac{X_{L0}}{3\omega} = \frac{X_{C0}}{3\omega} = \frac{1930}{3\omega} = 2H \tag{7.5}$$

The resistive losses are approximately 2.3 % and the local coil resistance thereby 15 Ω:

$$R_L = 0.025 \cdot X_L = 15.7\Omega \tag{7.6}$$

Provided a 10 kV system and a zero sequence voltage that equals the pre fault phase voltage the capacitive current generated from 5 km cable is approximately 9 A and the inductive and resistive current generated in the local coils are 9.2 and 0.2 A respectively:

$$3 \cdot I_{C0} = 3 \cdot \frac{10 \cdot 10^3}{\sqrt{3}} \cdot j\omega C_0 = 8.97A \tag{7.7}$$

$$I_L = 3 \cdot I_{L0} = \frac{10 \cdot 10^3}{\sqrt{3}} \cdot \frac{1}{R_L + j\omega L} = 0.23 - j9.18A \tag{7.8}$$

The local coils thereby generate a slightly too large inductive current to exactly compensate for the capacitive earth fault current generated in 5 km underground cable.

It has been found to be cost efficient to compensate for part of the cable capacitance by use of a central compensation coil as in conventional resonance earthed distribution systems (Elforsk 2006). In practice, all short cables and the part of the long cable feeders that are closest to the central busbar are therefore not equipped with local coils. If the central Petersen coil can be tuned, it can compensate for any over or under compensation of the local coils.

The current flow in the part of the cable that is not locally compensated, gives rise to resistive losses. These losses contribute to the resistive part of the equivalent zero sequence impedance and by that, the resistive earth fault current component. The size of the contribution depends on how far away from the busbar the local compensation starts, not on the total cable length. Figure 7.5 shows how the earth fault current varies depending on how far away from the busbar the local compensation starts. The figure shows the earth fault current contribution of a 50 km cable feeder during a solid earth fault on the busbar, but the variation is similar regardless of total cable length. In case of a 50 km cable, approximately 2.1 A of the current is not due to the current transportation, but to resistive losses in the local and the central Petersen coils.

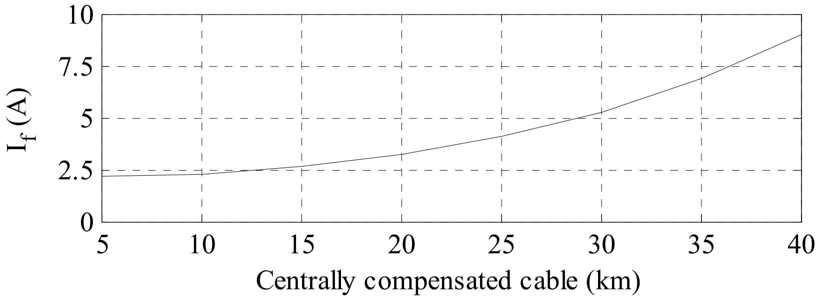

Figure 7.5 Earth fault current during a solid busbar fault in system with distributed compensation. The fault current depends on how far away from the busbar the local compensation starts. The distance between the coils is 5 km.

The current increase is not proportional to the distance between the busbar and the compensation coil, but becomes increasingly steep. From the calculated results it seems reasonable that 15 to 20 km of each cable feeder is compensated by the central Petersen coil, which is in accordance with guidelines provided by (Elforsk 2006).

The transformers

Early efforts with distributed compensation showed that local compensation coils do only behave as required if connected to transformers with low zero sequence impedance (Messing 2001). In addition, the compensation coils are connected to the transformer MV sides and the neutral point of both the transformer MV sides and LV sides must therefore be accessible for connecting earthing equipment. Standard transformers do not generally apply to these requirements and new transformers with integrated compensation coils have therefore been commissioned.

The Transfix Ecobloc transformer, which coil data is used in the calculations presented above, is a ZNdyn wound transformer (Transfix 2005). These transformers are more expensive than the standard transformer normally used for MV to LV transformation. The price ratio of a ZNdyn transformer compared to a standard transformer is approximately 2:1. Considering how large a part the transformer is of the entire station, this means that the cost ratio of the installations is in the order of 5:4 (Guldbrand et al. 2007).

Since the coil-equipped transformers involve an additional cost, it is desirable to only use these transformers when actually needed. At the same time, in order to keep the cost of the Petersen coil equipped transformers down, the transformers are only manufactured with a few different coil ratings. The distribution network operators that commission the transformers seem to have opted for one 10 kV rating and one 20 kV rating, both corresponding to local compensation at approximately every 5th km.

It is not obvious why the coils are dimensioned to compensate for 5 km. If the coils were instead dimensioned to compensate for 10 km, a smaller number of expensive transformers would be needed and according to the calculations presented in Figure 7.2, this does not give rise to considerably larger losses. However, one of the advantages associated with distributed compensation is that the degree of compensation does not change considerably if part of the system is disconnected. This advantage might not be utilized if the distance between each coil is as long as 10 km. In addition, the rating of the local coils was adjusted to be integrated in 100 kVA transformers, which are the most common transformer in urban distribution systems. Further, the size of the coils must be limited in order to facilitate selective HV and LV fuse function, i.e. to avoid unwanted MV fuse function due to the compensation current. Transformers with coil ratings according to the above can be used in systems with a nominal voltage of 10 kV without any risk of unwanted fuse function. More details on the ZNdyn transformer, its phase shifts, winding ratios, optimum coil size and calculated LV and MV currents during single, two and three phase faults can be found in (Guldbrand 2006a).

7.3 Mixed networks

In the process of replacing overhead lines with underground cables, some electrical distribution systems will most likely have feeders that combine overhead lines with underground cable. The part of the feeders that is underground cable has a strong capacitive connection to earth, while the overhead part has a weak capacitive connection to earth and an inductive equivalent impedance.

Central compensation

Figure 7.6 shows the simplified sequence network equivalent of an earth fault close to the busbar in a centrally compensated system that consists of a radial feeder with overhead line close to the busbar and cable further out. During an earth fault on the busbar or on the overhead line, the equivalent inductive impedance of the overhead line is connected in series with the capacitive impedance of the cable so that a series resonance circuit is formed.

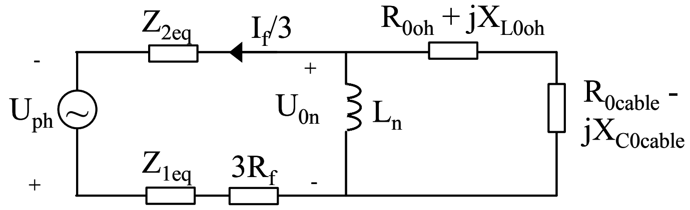

Figure 7.6 Simplified sequence network equivalent of an earth fault on the busbar of a resonance earthed system with a feeder that consists of overhead line and cable.

For series resonance to be reached, the inductive part of the equivalent overhead line impedance shall equal the capacitive part of the equivalent cable inductance. The inductance of the overhead line increases as the length of the overhead line increase while the capacitive part of the equivalent impedance decreases as the length of the cable increase. Consequently, a relatively long overhead line corresponds to a large series inductance, and does therefore require a relatively short cable for series resonance.

Figure 7.7 show the busbar earth fault current contributions of feeders that consist of overhead line closest to the feeder and cable further out. Provided zero sequence parameters according to Table 6.1, the cable required for fundamental frequency series resonance is 50 km if combined with approximately 80 km overhead line and 30 km if combined with approximately 140 km overhead line. Shorter cable parts require even longer overhead lines to show fundamental frequency resonant behaviour.

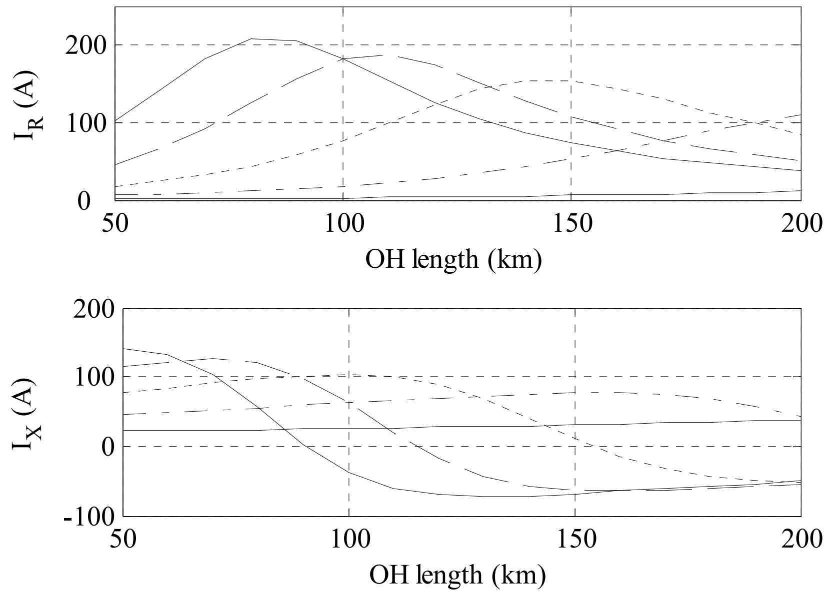

Figure 7.7 Resistive and reactive earth fault current contribution of radial feeders that consist of overhead line and cable. The length of cable is 50 km (solid line), 40 km (dashed), 30 km (dotted), 20 km (dash-dotted) and 10 km (solid).

The capacitance of the cable per km is larger than the inductance per km of the overhead line and the total series resonance length of the feeder therefore increases as the length of the cable decrease. This means that the equivalent resistance of the resonant circuit is larger in systems that consist of short cables and long overhead lines than in systems that consist of long cables and short overhead lines. During resonance, the resistance alone limits the fault current and the peak current is therefore larger, the larger cable part.

If both overhead line and cable parts of the feeder are extensive enough, the reactive part of equivalent impedance and the earth fault current contribution is inductive. An inductive current cannot be compensated for by use of Petersen coils, a bank of capacitors will instead be necessary. Figure 7.8 shows the fault current during a busbar earth fault in a conventionally resonance earthed system that consists of one long feeder of varying length. The feeder has overhead line close to the busbar and cable further out.

Because of the series resonance, feeders that are combinations of overhead line and cable might have low, solely resistive equivalent impedance. The resistive part cannot be compensated for by use of a central Petersen coil or capacitors, and the resulting resistive earth fault current might therefore be extensive during low-impedance earth faults.

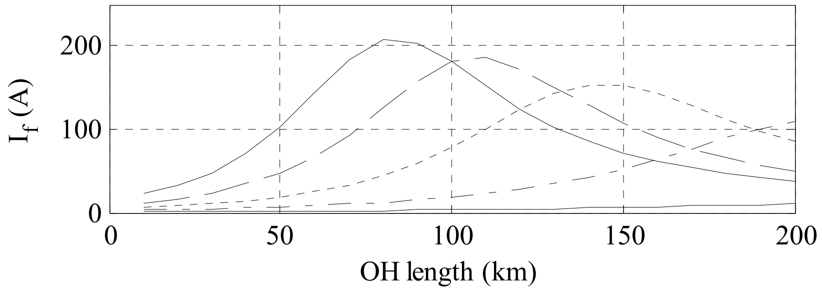

Figure 7.8 Fault current amplitude during a busbar earth fault in a resonance earthed system. The length of cable is 50 km (solid line), 40 km (dashed), 30 km (dotted), 20 km (dash-dotted) and 10 km (solid).

The low equivalent impedance does also influence the high-impedance earth fault detection. Figure 7.9 shows the neutral point displacement voltage during a busbar fault in systems with combined overhead line and cable feeders. The neutral point displacement reaches values as low as 2 % of the pre fault phase to earth voltage. This implies that the earth faults might be hard to detect by use of conventional voltage relays.

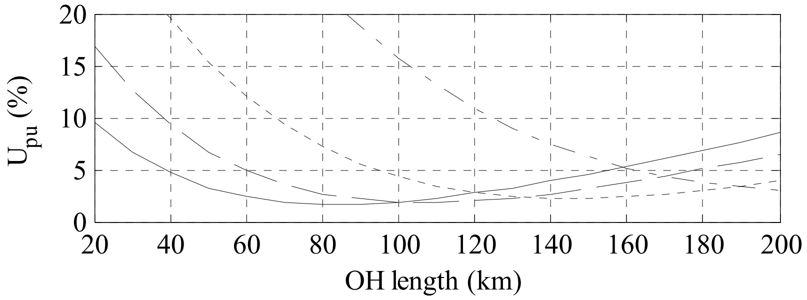

Figure 7.9 Neutral point displacement voltage during a 5 kΩ busbar earth fault in a resonance earthed system. The length of cable part is 50 km (solid line), 40 km (dashed), 30 km (dotted) and 20 km (dash-dotted).

Distributed compensation

The equivalent impedance of a locally compensated cable is very high and locally compensated cables will therefore not cause series resonance if connected in series with inductive overhead lines. However, if part of the feeder is not locally compensated, its equivalent impedance is capacitive. The equivalent capacitance does not depend on the total cable length, but on the length of the cable that is not locally compensated.

Figure 7.10 show the busbar earth fault current contribution of feeders that consist of overhead line followed by cable that is only partially locally compensated. The total cable length is 40 km. The local compensation of the cable starts 10, 15 or 20 km from the overhead line. Additional cable is compensated by a central coil.

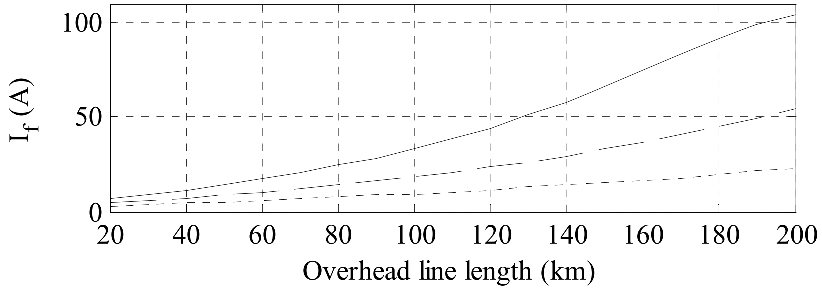

Figure 7.10 Magnitude of earth fault current in partially locally compensated system. The local cable capacitance compensation starts 10 (dotted), 15 (dashed) or 20 (solid line) km from the end of the overhead line.

The calculated results suggest that if very long feeders consist of overhead line section close to the busbar and underground cable section further out, the local cable capacitance compensation shall start as close to the overhead line part section of the feeder as possible.

7.4 Branched cable feeders

In practice, distributed compensation has been implemented in branched systems rather than systems with very long strictly radial feeders. Local coils increase the equivalent shunt impedance of the parallel-connected feeders. The series impedance is thereby very small compared to the shunt impedance, and the resistive part of the equivalent impedance of the system will mainly be due to resistive losses in the Petersen coils.

7.5 Parameter sensitivity

In conventional distribution systems, cable feeders are relatively short and the underground cable series impedance therefore negligible. Consequently, it has not been of any particular interest to know the exact value of the underground cable zero sequence series impedance z_0. However, the series impedance does influence the earth fault behaviour in systems consisting of long cables and consequently the impedance size is of considerable importance to the accuracy of the earth fault analysis of these systems.

In addition, the series impedance varies depending on the dimensions and installation of the cables, and hence the influence of zero sequence series impedance variations on the earth fault behaviour is of important for the understanding of the system (Tziouvaras 2006). In this work the underground cable zero sequence series impedance resistance is assumed to be 1.5 Ω/km and the corresponding inductance 2 mH/km. Figure 7.11 and Figure 7.12 show how a 40 % increase or decrease of the resistance and impedance respectively, influence the maximum fault current contribution of a long cable feeder.

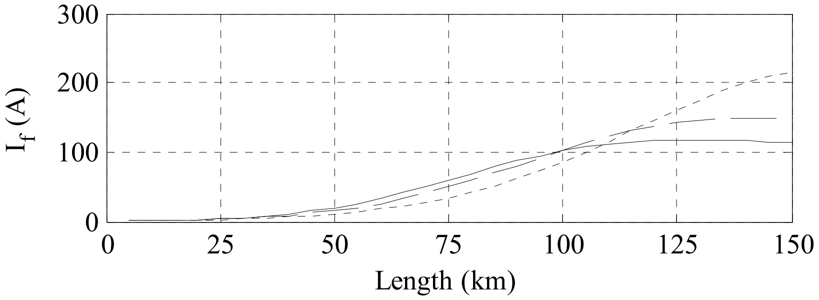

Figure 7.11 Calculated maximum earth fault current in a resonance earthed system consisting of one cable feeder. The zero sequence series resistance is set to 0.9 Ω/km (dotted) 1.5 Ω/km (dashed) and 2.1 Ω/km (solid line).

The influence of the variations of the series resistance depends on the cable length. If the cable length is such that the reactance is very dominating, low series impedance will give a low resistive current and vice versa. As the cable length is increased to resonance length, low cable zero sequence series resistance will instead result in a higher resistive fault current than high cables zero sequence series resistance. This is because the reactance is very small and the resistance constitutes the main part of the equivalent impedance. The influence of the series impedance can also be explained in terms of resonance damping. A large series resistance will damp the resonance. This means the resonance curve is flattened so that the maximum earth fault current is decreased, while the earth fault current in systems where the inductance and capacitance is not of the same size, is increased.

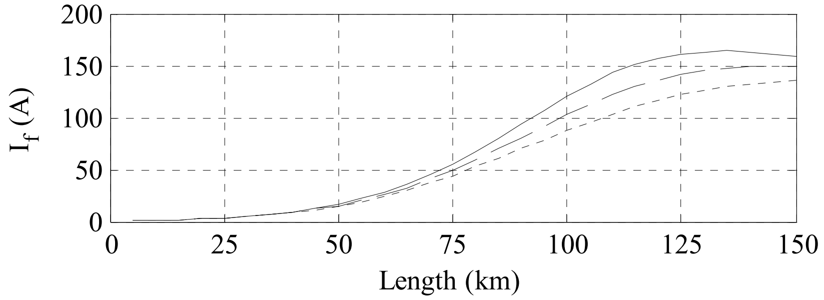

Figure 7.12 Calculated maximum earth fault current in a resonance earthed system consisting of one cable feeder. The zero sequence series impedance is set to 1.2 mH (dotted), 2 mH (dashed) and 2.8 mH (solid line).

The shunt capacitance of the cables contributes to a large capacitive component of the equivalent zero sequence impedance. The zero sequence series inductance reduces the resulting capacitive reactance of the cable feeders. The reduction is larger, the larger the series inductance (until resonance is reached). Consequently, the earth fault current contribution of cables with large series inductance is larger than the contribution of cables with small series inductance. The size of the series inductance does also influence the wave properties of the cable and thereby the length at which the maximum fault current is reached.

The zero sequence series resistance does also influence the high-impedance earth fault detection. Figure 7.13 shows the neutral point displacement voltage during a 5 kΩ fault in a conventionally resonance earthed system. The calculations show that increasing series impedance will give a decreasing neutral point displacement voltage. The influence of the zero sequence inductance on the neutral point displacement voltage is negligible.

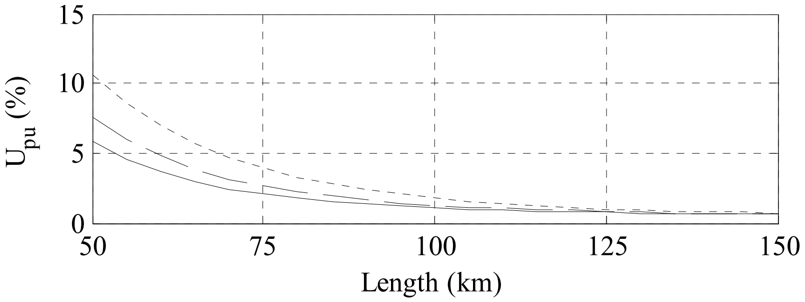

Figure 7.13 Calculated neutral point displacement voltage during 5 kΩ earth fault in a resonance earthed system consisting of one cable feeder. The zero sequence series resistance is set to 0.9 Ω/km (dotted) 1.5 Ω/km (dashed) and 2.1 Ω/km (solid line).

Local compensation decreases the influence of the series impedance. Consequently, neither variation of the zero sequence series resistance nor variation of the zero sequence series inductance, influence the earth fault behaviour to any considerably extent.

Chapter 8

Zero sequence impedance

From the previous chapter it is clear that the value of the zero sequence series impedance influences the earth fault behaviour of systems with long cables but since it does not influence the earth fault behaviour of conventional systems, its value has not previously been of particular importance. There are therefore considerable uncertainties associated to zero sequence impedance calculation methods and how its values depend on cable installation.The zero sequence impedance of underground cables is not only determined by the series impedance, but also by the zero sequence capacitance. The zero sequence capacitance is however not associated to the same level of uncertainties as the zero sequence series impedance and is therefore not treated in this chapter.

Many publications on methods to calculate the zero sequence series impedance of underground cables have been published. Among the published methods, are models supplied from cable manufacturers (Ericsson), (Nexans 2008) and a, among Swedish utilities widely spread, method that calculates the zero sequence impedance of cables with return path in screen or additional earth wire (Henning). In these models, the zero sequence series impedance depends on cable dimensions as well as installation. The cable dimension dependency can be included in general calculations and be measured by cable manufacturers while the installation dependency means that the zero sequence impedance of a specific type of cable differs between different cable installations.

8.1 Flux based zero sequence cable model

The zero sequence series impedance analysis in this work is based on a mathematic model of a three-phase underground cable and general flux equations. The flux equations are derived from (Rønne-Hansen 1994) and are previously treated in (Guldbrand 2006c) and (Guldbrand et al. 2008).

Figure 8.1 shows important cable and installation properties of an underground cable. In this work, the zero sequence series impedance is calculated for earth faults between phase and screen. The zero sequence current returns in the screen I_{sc}, an additional earth wire I_{ew} and via earth I_e.

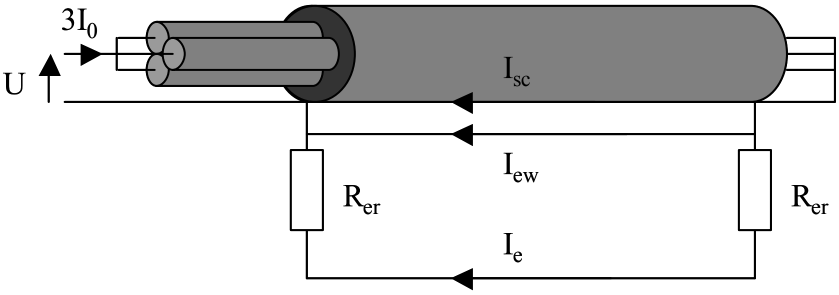

Figure 8.1 Installed three-phase underground cable with some important cable and installation properties. The same voltage U is applied to all three phases. In the other cable end, the three conductors are connected to the screen.

The zero sequence impedance Z_0 is the impedance that limits the current I_0 (in each phase conductor) when the same voltage source U is connected to all three phases:

$$Z_0 = \frac{U}{I_0} = \frac{3U}{I_{sc} + I_{ew} + I_e} \tag{8.1}$$

The zero sequence series impedance depends on the self and the mutual impedance of the current paths, which in turn depends on the cable dimensions and on the properties of the return paths. Figure 8.2 shows the dimensions of a three-phase cable and an additional earth wire. The cable has three conductors, each of radius r_c, insulation of varying thickness and a screen. The radius of the cable is denoted r_{sc} in the figure. The resistivity of the conductors and the screen depend on the cross-sectional areas and the conducting material. The conductors, as well as the screen, are often made of copper. The installation includes an additional copper wire which decreases the resistance of the return path. The distributed resistive connection between the copper wire and earth can be modelled by an arbitrary number of resistive connections, see for example (Popovic 2007) or (Guldbrand 2006c). Such representation does not significantly influence the results presented in this work.

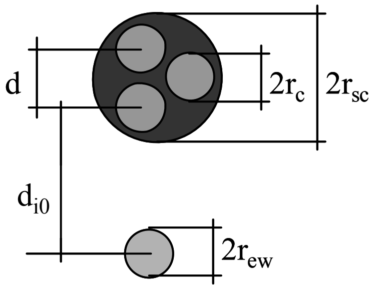

Figure 8.2 Three-phase cable with additional earth wire.

The conductor and return paths form three circuits: conductors and screen, conductors and earth wire and concoctors and earth. The current circuits create self and mutual impedances:

$$Z = R_{matrix} + jX_{matrix} \tag{8.2}$$

$$R_{matrix} = \begin{pmatrix} R_{sc} + R_c & R_c & R_c \\ R_c & R_{ew} + R_c & R_c \\ R_c & R_c & 2R_{er} + R_c \end{pmatrix} \tag{8.3}$$

$$X_{matrix} = \frac{\omega\mu_0}{2\pi} l \cdot \begin{pmatrix} ln\frac{r_{sc}^2}{r'_{sc}r'_c} & ln\frac{d_0 r_{sc}}{d_0 r'_c} & ln\frac{D_e r_{sc}}{D_e r'_c} \\ ln\frac{d_0 r_{sc}}{d_0 r'_c} & ln\frac{d_0^2}{r'_{ew}r'_c} & ln\frac{D_e d_0}{D_e r'_c} \\ ln\frac{D_e r_{sc}}{D_e r'_c} & ln\frac{D_e d_0}{D_e r'_c} & ln\frac{D_e^2}{r'_e r'_c} \end{pmatrix} \tag{8.4}$$

The resistance matrix consists of screen resistance R$_{sc}$, conductor resistance R$_c$, earth wire resistance R$_{ew}$ and resistance to earth R$_e$. The inductive part of the impedance matrix depends on cable dimension and equivalent penetration depth D$_e$. Since the voltage along each circuit equals U, the zero sequence impedance includes the inverse of the sum of all inverse matrix elements:

$$Z_0 = \frac{U}{I_0} = \frac{3U}{I_{sc} + I_{ew} + I_e} = \frac{3}{\sum_{i=1}^{3}\sum_{j=1}^{3} Z_{ij}^{-1}} \tag{8.5}$$

If either the influence of the screen or the influence of the additional earth wire is neglected, the results from the above equations are in accordance with the results obtained from (Henning).

In this work, the model is used to study how the conductor and screen areas, earth wire and resistance to earth influence the zero sequence series impedance. Since the work concerns long cables, it is of particular interest to see how the length of the cable influences the series resistance and reactance. The cable and installation parameters are varied one by one. When not being the variable parameter, they are assigned values according to Table 8.1.

Table 8.1 Cable and installation properties.

Conductor area	Screen area	Earth wire distance	Resistance to earth R_e
95 mm^2	25 mm^2	0.1 m	10 Ω

Figure 8.3 shows the resistive and inductive parts of the zero sequence series impedance calculated with parameter values according to Table 8.1. It is clear that the length of the cable influences the resistive as well as the inductive components.

Since the resulting resistance to earth is assumed constant and independent of cable length, the zero sequence impedance per km depends on the length of the cable. The proportional influence of the resistance to earth decreases as the length of the cable increases and the return path resistance per km thereby decreases. This also means that a larger part of the current will return via earth and the inductance is therefore slightly increased. When the length of the cable has reached approximately 40 or 60 km the resistance to earth is very small compared to other sources of impedance and does not significantly influence the zero sequence impedance of the cable installation.

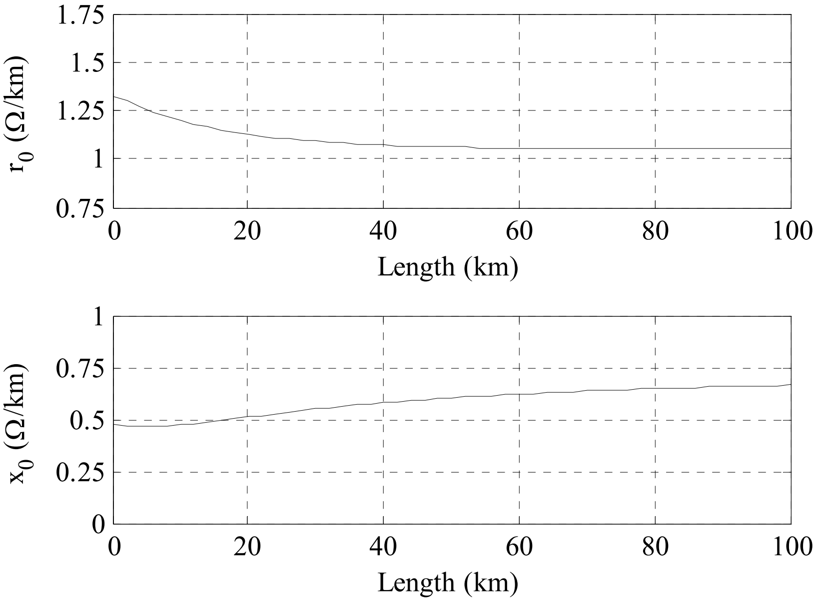

Figure 8.3 Zero sequence impedance per km for a cable installation with properties according to Table 8.1.

8.2 Influence of cable dimensions

An increased conductor or screen cross-sectional area decreases the current path resistance and by that the resistive component of the zero sequence impedance. The dimension of the conductors and the screen is however limited by practical and economical reasons.

Figure 8.4 shows the influence of the conductor cross-sectional area. An increase of the area from 50 to 95 mm^2 decreases the resistive component much more than an increase from 95 to 150 mm^2 and hence changes in conductor area seem to be of more importance to the impedance of relatively small conductors. Since the area of the conductors does not influence the current return path, the inductive component is not to any considerable extent influenced by changes of conductor area.

Figure 8.5 shows the influence of the screen area on the zero sequence impedance. In addition to a decreased series resistance, an increased screen area decreases the series inductance. This is because a larger part of the earth fault current returns through the screen, which is associated with lower inductance compared to the earth or earth wire return paths.

The zero sequence series resistance used in the circuit analysis in previous chapters is 1.5 Ω, which is rather high compared to the values in Figure 8.4 and Figure 8.5. The same applies to the zero sequence series inductance, which is assigned 2 mH in the circuit analysis. For 50 Hz, 2 mH corresponds to a reactance of 0.63 Ω.

The cable dimensions are well known and their influence on the electric parameters of the cable can be included in general cable data provided by manufacturers.

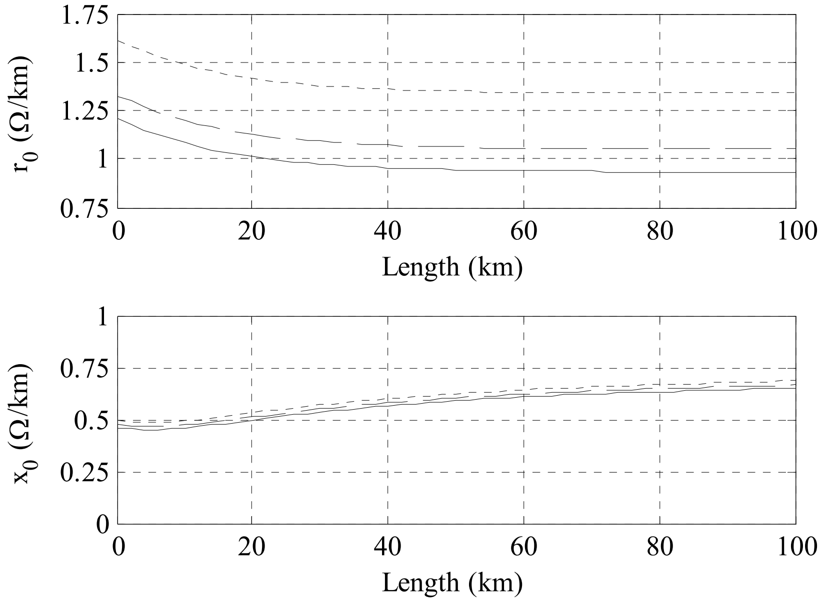

Figure 8.4 Zero sequence series resistance and reactance calculated for conductor area 50 (dotted), 95 (dashed) and 150 (solid) mm^2. The cross-sectional area of the additional earth wire is 35mm^2.

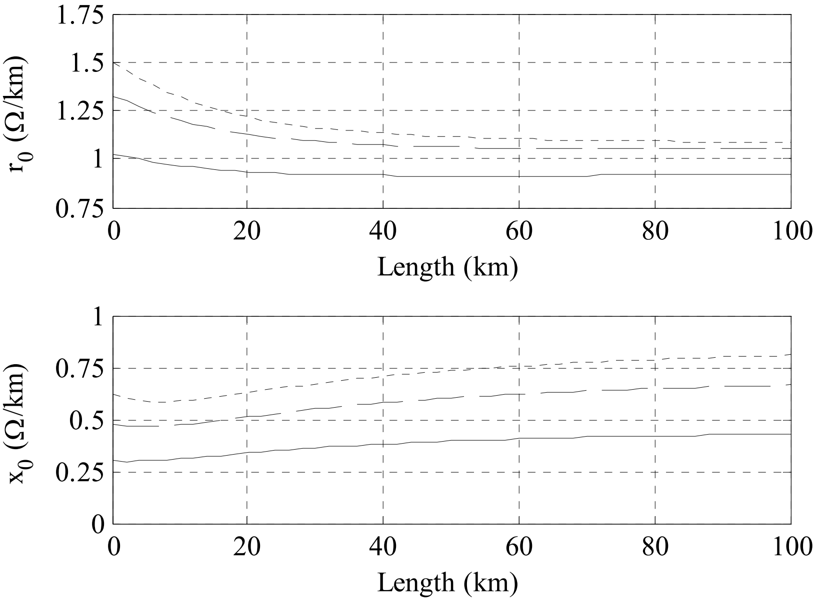

Figure 8.5 Zero sequence series resistance and reactance calculated for screen area 16 (dotted), 25 (dashed) and 50 (solid) mm^2.The area of the additional earth wire is $35mm^2$.

8.3 Influence of cable installation

Some installation parameters, for example the additional copper wire sometimes installed with the cables, can be easily documented and its influence on the series impedance can thereby be calculated relatively easily and accurately. Figure 8.6 shows the influence of an additional 35 mm^2 copper wire on the zero sequence impedance of the installation.

Since the copper area is not changed, the series resistance is not much influenced by the distance between the copper wire and the cable. The inductance will however increase as the copper wire is moved away from the conductors. If the additional copper is put in the screen instead of as an additional wire, the return path is very close to the conductors and the inductance decreases further. This solution would also influence other, practical, aspects such as the cable laying.

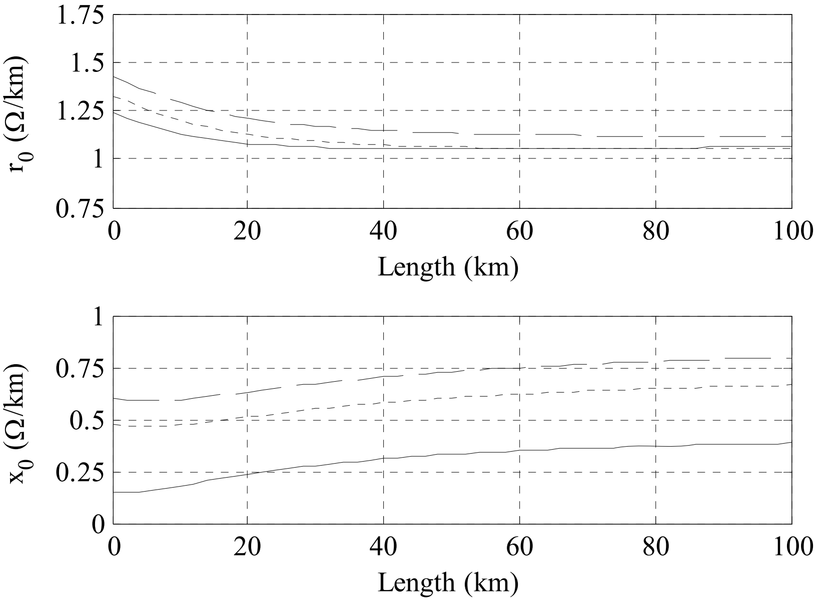

Figure 8.6 Zero sequence series resistance and reactance calculated for installations with a 35 mm^2 copper wire located 0.1 m (dotted) and 0.5 m (dashed) from the cable. The solid line shows the parameters if the 35 mm^2 copper is instead added to the screen.

The calculated zero sequence impedance presented in Figure 8.6 assumes relatively short distances between the cable and the additional earth wire. There are arguments that they should be further apart in order to increase the probability for the additional wire to stay intact in case of excavation faults (Guldbrand 2006c). However, if the additional wire is located further from the cable, its influence on the zero sequence impedance will be very small.

Contrary to properties of additional earth wires, the resistance to earth is, as mentioned in Chapter 2, not exactly known to the network operators. In the cable model used in this work, the screen and the additional earth wire of the cable of interest are not included in the resistance to earth, and the resistance is therefore set somewhat higher than the 5 Ω mentioned in Chapter 2. Figure 8.7 shows the influence of the size of the resistance to earth. The resistance is set to 5, 20 or 50 Ω, which all differ from the value used in the zero sequence series impedance calculations above.

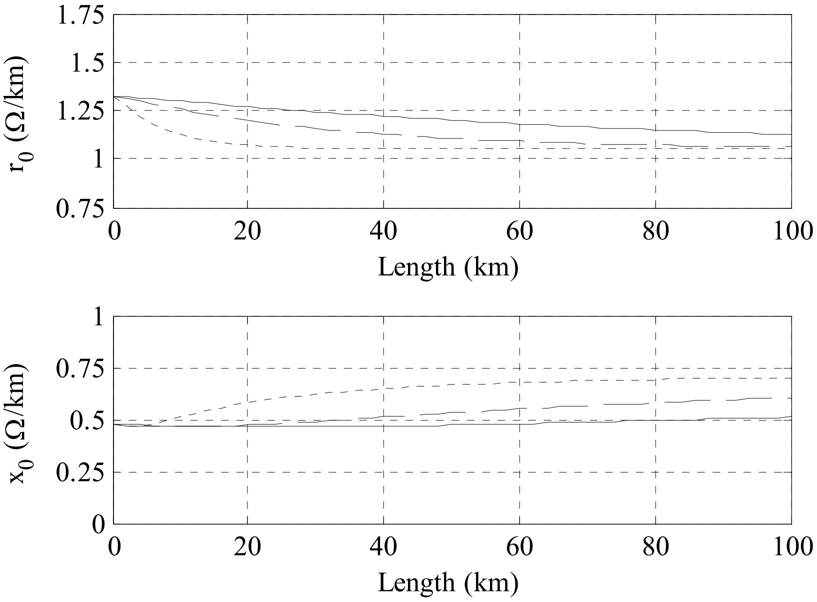

Figure 8.7 Zero sequence series resistance and reactance calculated if the resistance to earth is 5 (dotted), 20 (dashed) and 50 (solid) Ω.

The influence of the resistance to earth depends on the cable length and the size of the resistance. For very short cables, all values assigned to the resistance to earth are too high for any considerable amount of the fault current to return through earth.

If the other cable and installation parameters are according to Table 8.1, the series resistance will be considerably smaller than the 1.5 Ω that is used in the circuit analysis above, regardless of the resistance to earth.

8.4 Discussion

The calculations above show that the series impedance depends on the cable length. In most computer programs, the zero sequence impedance is specified as Ω per km. If these programs are used the specified value should, according to the results above, be varied depending on the length of the modelled cable.

The zero sequence series impedance depends on dimensions as well as installation. The dimensions, and to some extent the installation can be adjusted to achieve required electric data. Possible cable construction and installation properties are however limited by financial and practical aspects. (Guldbrand 2007) provides some thoughts about cable laying and asset management that are not in the scope of this work.

This work does not include any measurements of the zero sequence impedance of long cables. Measurements are very important to assess the results of the impedance calculations. Since the series impedance seems to depend on cable length, the measurements shall be performed on installed cables of varying length. Before the measurements, it must be clear what properties are measured. Depending on the cable length and the cable connection, the measured quantities might not only depend on the zero sequence impedance but they might also be influenced by the capacitive connection between the cable and earth.

Chapter 9

Time simulations

Circuit analysis as that carried out in the previous chapters is one of several methods for power system analysis. One alternative or complementary approach is analysis by time simulations. There are several computer programs available for time simulations. Two of the most popular programs are PSCAD/EMTDC (Manitoba 2005) and Matlab SimPowerSystems (MathWorks 2008). The time simulations in this work are preformed by use of Matlab SimPowerSystems. Matlab SimPowerSystems can be used for transient time simulations as well as fundamental frequency time simulations. However, the models required for adequate transient time simulations are more sophisticated than the models required for the fundamental frequency simulations carried out in this work.

Within this work, time simulations are used to verify that the results obtained from the sequence network calculations are not affected by the related simplifications. Other purposes are to analyse the influence of the transformer impedance on the earth fault behaviour of the systems and to calculate the earth fault behaviour of some additional distribution system designs.

9.1 Assessment of sequence network calculations

The accuracy of the simulated results depends on the integration routine and on the accuracy of the parameters used to model the system components. There are no specific three-phase cable models in SimpowerSystems, or in EMTDC. The transmission lines are instead represented by sequence parameters and pi-sections. Since the time simulations shall be used to evaluate the results obtained from the circuit analysis, the transmission line parameters are in accordance with those in the sequence network representation. The nominal voltage is set to 10 kV and the source and transformer impedances are neglected. The sequence parameters of cables and overhead lines are shown in Table 9.1.

The sequence parameters are often associated to a considerable degree of uncertainty. The accuracy of the simulations might therefore improve by use of specific cable models and support programs that help calculating the electrical parameters from cable dimensions and installation properties. According to (Gustavsen et al. 2005) such solutions are common in electromagnetic transient programs (EMTP).

Table 9.1 Cable and overhead line sequence parameters, similar to Table 6.1.

	Series resistance r	**Series inductance l**	**Shunt capacitance c**
Cable			
Positive and negative seq.	0.32 Ω/km	0.3 mH/km	0.33 μF/km
Zero seq.	1.5 Ω/km	2 mH/km	0.33 μF/km
Overhead line			
Positive and negative seq.	0.52 Ω/km	1.3 mH/km	9.95 nF/km
Zero seq.	0.67 Ω/km	6.4 mH/km	4.4 nF/km

In order to assess the results obtained from the circuit analysis, models of resonance earthed systems that each consists of one cable feeder have been constructed and the earth fault behaviour of the systems have been simulated. The inductance of the simulated Petersen coils is 105 % of the capacitive inductance of the feeder. The tuning of the coil is thereby in accordance with that used in the circuit analysis. The simulated and calculated maximum earth fault currents of the systems are compared in Figure 9.1. The simulated current is similar to the current calculated by use of sequence networks.

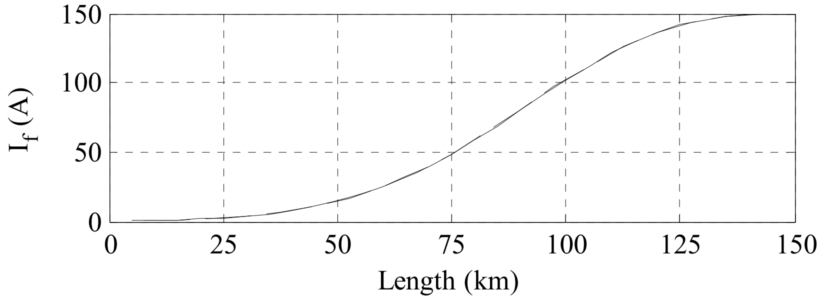

Figure 9.1 The simulated and analytically calculated earth fault current amplitudes overlap during earth fault on the HV to MV transformer busbar in distribution systems consisting of one cable feeder.

The simulated and the calculated 5 kΩ earth fault neutral point displacement voltage are compared in Figure 9.2.

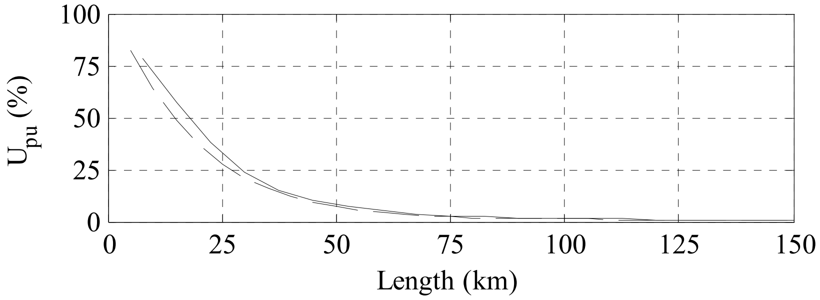

Figure 9.2 Simulated (solid line) and calculated (dashed line) neutral point displacement voltage during 5 kΩ earth fault. The voltage is related to the pre fault phase voltage.

The simulated voltage, as the rest of the simulated results, is in accordance with that calculated by use of sequence networks. The results thereby confirm that for fundamental frequency analysis, sequence network calculations are as accurate as time simulations.

9.2 Influence of transformer impedance

Network models with negligible transformer impedance are accurate for the understanding of the earth fault behaviour in electric distribution systems. However, if precise magnitudes are of interest, it is necessary to include the transformer impedances in the models.

Yyn-wound three-phase transformers are commonly used for HV to MV transformation in Swedish distribution systems. The transformers typically have zero sequence impedance that is 5 to 10 times the positive sequence impedance (Akke 2006). The thee-phase transformer models available in SimPowerSystems consist of three connected single-phase transformers, which cannot be assigned parameters that are in accordance with that of the Yyn-wound three-phase transformers. In this work, the voltage source and Yyn-wound transformer is instead represented by a 10 kV voltage source and an additional zero sequence impedance as shown in Figure 9.3.

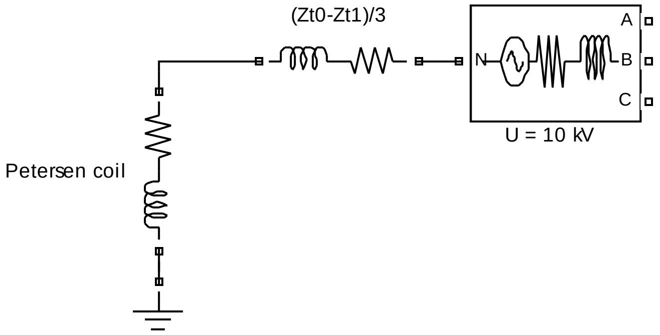

Figure 9.3 Transformer modelled by a voltage source and additional zero sequence impedance connected to a Petersen coil. The nominal voltage is 10 kV.

The positive and zero sequence transformer impedances vary considerably depending on the transformer design. The impedances used to model the HV to MV transformer in this work are based on data used in previous studies (Elforsk 2006) and field test results (Akke 2006). The zero and positive sequence transformer impedance as well as the impedances assigned to the source and the additional zero sequence impedance simulation models, are listed in Table 9.2.

Table 9.2 Transformer sequence impedance and corresponding model parameters.

Positive sequence impedance	**Zero sequence impedance**	**Source impedance**	**$(Z_{t0}$-$Z_{t1})/3$**
0.008 + j1.2 Ω	3.6 +j12 Ω	0.008 + j1.2 Ω	1.2 + j3.6 Ω

The size of the central Petersen coil model varies depending on the tuning. In this work, the simulated losses of the central Petersen coil are 2 % and there is no additional neutral point resistor in the systems.

The zero sequence impedance together with the current generated in the Petersen coil give rise to a voltage drop between the busbar and the transformer neutral point. The voltage drop is proportional to the size of the fault current. The current is large during low-impedance faults in systems with extensive use of cable and the neutral point displacement voltage might therefore be considerably different from the busbar zero sequence voltage.

Busbar fault

The neutral point displacement voltage does not only depend on the voltage drop across the transformer impedance but also on the zero sequence voltage at the busbar. If the earth fault is located close to the busbar, the busbar zero sequence voltage equals the pre fault phase voltage. This means that the total difference between phase voltage and neutral point displacement voltage proportional to the compensation current:

$$U_{0n} = U_{0b} - I_L \cdot \frac{Z_{t0}}{3} = U_{ph} - I_L \cdot \frac{Z_{t0}}{3} \tag{9.1}$$

$$U_{ph} - U_{0n} = I_L \cdot \frac{Z_{t0}}{3} \tag{9.2}$$

If the Petersen coil is tuned for busbar faults, the current generated in the Petersen coil during a busbar fault is proportional to the equivalent zero sequence capacitance of the system:

$$I_L \propto I_C = U_{0b} \cdot \omega C_{0ekv} = U_{ph} \cdot \omega C_{0ekv} \tag{9.3}$$

The constant of proportionality depends on the degree of the tuning.

During a busbar earth fault the difference between the phase voltage and the neutral displacement voltage phase is thereby proportional to the equivalent zero sequence capacitance of the system, and the constant of proportionality depends on the transformer impedance:

$$U_{ph} - U_{0n} \propto \frac{Z_{t0}}{3} U_{ph} \omega C_{0ekv} \tag{9.4}$$

Figure 9.4 show the simulated current generated in the Petersen coil and the neutral displacement voltage. The inductive current and the voltage decrease are proportional to the equivalent zero sequence capacitance of the system. The equivalent capacitance and the Petersen coil current reach maximum and the neutral point voltage reach minimum, as the length of the cable is approximately 100 km. As long as the transformer zero sequence impedance is small compared to the impedance of the Petersen coil it does not influence the equivalent resistance of the system or the resistive maximum earth fault current.

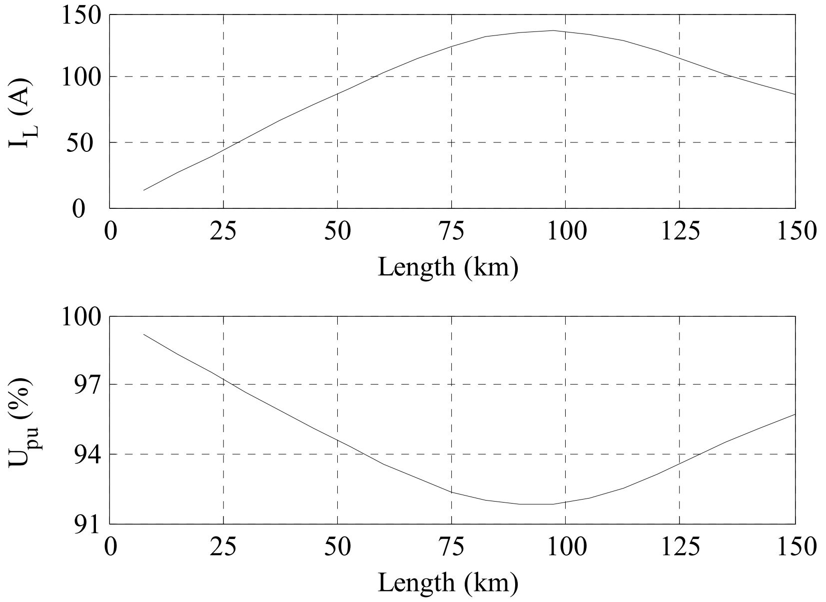

Figure 9.4 Simulated Petersen current magnitude and neutral point voltage for a solid earth fault at the busbar.

Cable fault

During a solid earth fault located far away from the busbar, the busbar zero sequence voltage will not equal the phase voltage. The difference between the pre fault phase voltage and the neutral point displacement voltage includes the voltage drop across the transformer impedance as well as the voltage drops across the positive, negative and zeros sequence series impedances of the rest of the system.

Figure 9.5 shows the simulated Petersen coil current, neutral point voltage and busbar zero sequence current for a solid end of line earth fault. Neither the current nor the neutral point displacement voltage or zero sequence voltage at the busbar are proportional to the equivalent zero sequence capacitance of the system. The voltage drop across the transformer zero sequence impedance is proportional to the Petersen coil current, but the neutral point displacement voltage does not reach a minimum as the length of the cable increase. This is because the equivalent impedance of the system and by that the voltage drop along the cable, increases as the length of the cable increase.

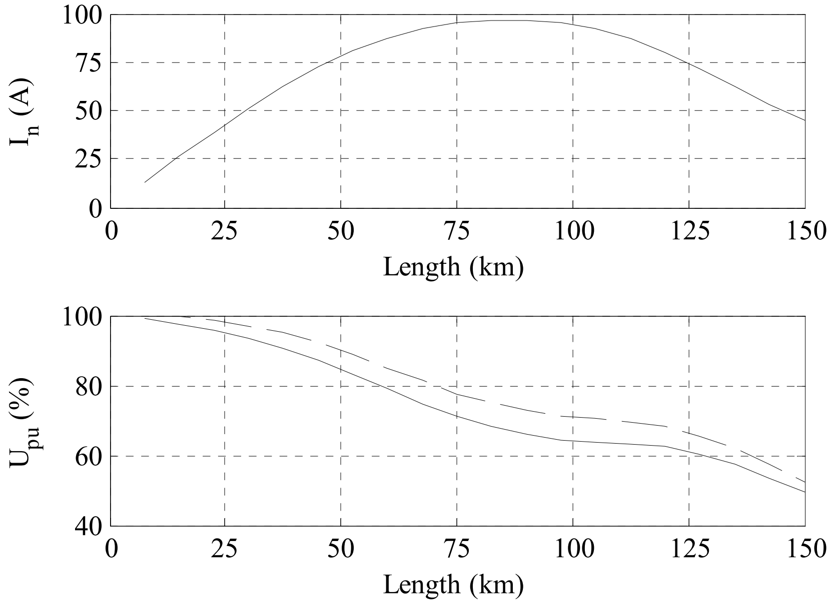

Figure 9.5 Simulated Petersen coil current magnitude, busbar zero sequence voltage (dashed) and neutral point voltage (solid). The simulated earth fault is solid and located at the end of the cable.

Multiple feeders

The current generated in the compensation coil in resonance earthed distribution systems with multiple cable feeders, shall compensate for the capacitive current generated in all cable feeders. Since the voltage drop across the transformer impedance is proportional to the compensation current, the difference between the busbar zero sequence voltage and the neutral point voltage is proportional to the total capacitive current generated in all cable feeders.

Insufficient compensation

If the zero sequence impedance of the transformer is large and the total cable length extensive, the voltage drop across the transformer is considerable and the neutral point displacement voltage might therefore be very low. Since the inductive current generated in the coil is proportional to the neutral point voltage, it is possible that a low neutral point voltage could lead to difficulties to generate a large enough compensation current during the earth faults. The zero sequence impedance of small transformers is in general larger than that of large transformers. The possibility to generate sufficient inductive compensation current might therefore set a limit for the minimum size of the transformers in electric distribution systems with extensive use of cables.

High-impedance fault detection

The high-impedance fault neutral point displacement voltage is only moderately affected by the transformer impedance. In Figure 9.6, the neutral point voltages simulated for 5 kΩ faults in models including transformer impedance are compared to the corresponding voltages simulated in systems without transformer impedance.

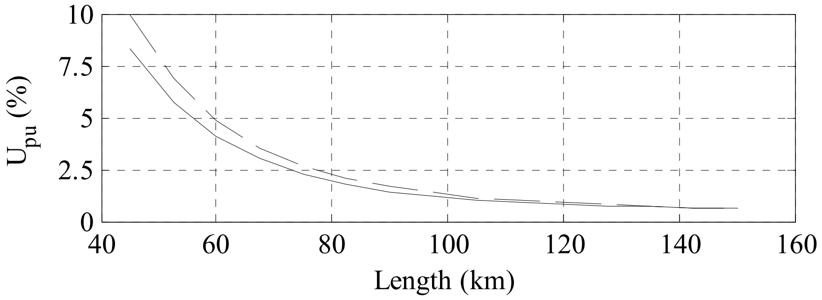

Figure 9.6 Neutral point displacement voltage simulated in systems modelled with transformer impedance (solid line) and simulates in systems without transformer impedance (dashed). The fault resistance is 5 kΩ.

As the length of the cable increases, the influence of the transformer impedance decreases. This is because the equivalent zero sequence impedance of the system is very small compared to the fault impedance and the relation between them are thereby barely influenced by the transformer impedance.

9.3 Local compensation coils

In order to properly simulate the earth fault behaviour in systems with distributed compensation, the local compensation coils and the MV to LV transformers must be accurately modelled. The locally compensated systems modelled in this work are equipped with compensation coils and transformers that are based on a Transfix Ecobloc 100 kVA transformer (Transfix 2005). Each transformer includes a compensation coil that is dimensioned to approximately compensate for the capacitive current generated in 5 km cable. This is in accordance with the local coils modelled in the sequence network calculations in Chapter 7. The coil parameters, and the total positive and zero sequence impedances of the SimpowerSystems MV to LV transformer model are shown in Table 9.3.

Table 9.3 Sequence parameters of 100 kVA ZNdyn transformer and local coil.

Coil impedance	Zero sequence impedance	Positive sequence impedance
15 + j628 Ω	20 + j630 Ω	0.033 + j0.065 Ω

Each three phase ZNdyn transformer is modelled by three four winding single-phase transformers connected to an additional zero sequence impedance, as shown in Figure 9.7.

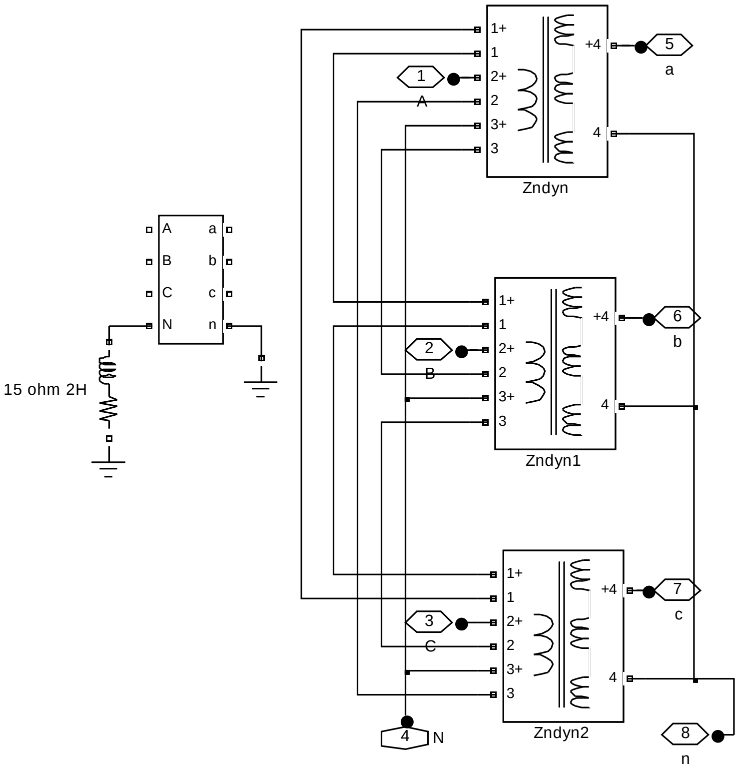

Figure 9.7 Schematic figure of MV to LV transformer model connected to the distributed compensation coil (left) and the transformer in detail (right)

In the simulated systems, the 20 km cable closest to the busbar is not equipped with local compensation. Instead, a central Petersen coil generates inductive current to compensate for the capacitive current contribution of this part of the cables. The inductance of the central coil is 105 % of the resonance inductance, including local compensation.

Figure 9.8 shows maximum earth fault current amplitudes in systems consisting of one long locally compensated cable. The figure shows the busbar earth fault currents as well as the fault currents during earth faults located at the end of the cable.

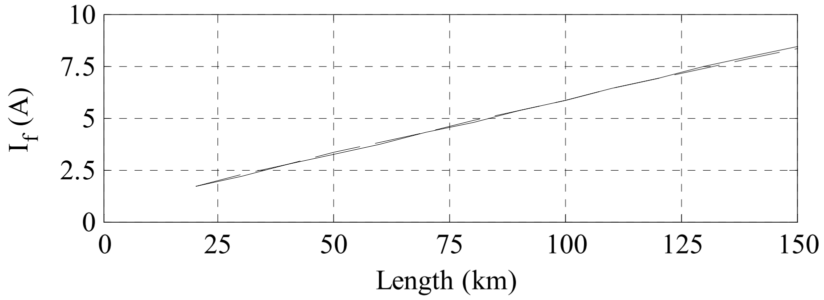

Figure 9.8 Earth fault current magnitude in locally compensated system consisting of one cable radial of varying length. The difference between the fault current during an earth fault on the busbar (solid) and at the end of the cable (dashed) is negligible.

As explained in Chapter 7, the influence of the zero sequence series impedance is small in systems with local compensation. If the zero sequence impedance is negligible, the resistive solid earth fault current is only due to resistive losses in the Petersen coils. Since the losses are proportional to coil size and the coil size in a resonance earthed systems is proportional to the length of the compensated cable, the resistive losses, and by that the maximum earth fault current, is proportional to cable length. The transformer impedances, which are neglected in the sequence network calculations, somewhat increase the losses and thereby the resistive earth fault current. However, the simulated results are overall in accordance with the calculated results; local compensation clearly reduces the earth fault current.

The simulated neutral point displacement voltage during 5 kΩ earth faults in systems with distributed compensation is shown in Figure 9.9. Since the equivalent zero sequence impedance of locally compensated systems is larger than that of centrally compensated systems, the high-impedance fault neutral point voltage does not reach as low values as is the case for system with central compensation.

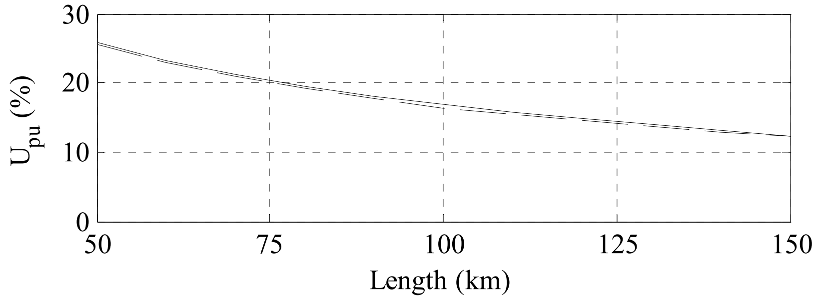

Figure 9.9 Neutral point displacement voltage during a 5 kΩ earth fault in locally compensated system. The difference between the voltage during an earth fault on the busbar (solid) and at the end of the cable (dashed) is negligible.

The current generated in the central Petersen coil only compensates for the 20 km cable closest to the busbar and the voltage drop across the HV to MV transformer impedance is therefore limited. Providing cables whose lengths exceed 20 km, the voltage drop is only proportional to the number of cables and not to the cable length.

9.4 Branched cable feeders

Time simulations can be used to analyse earth faults in electric distribution systems with considerably more complicated network configurations than strictly radial feeders. In this chapter, the results of simulated earth faults in branched systems are presented.

First, a resonance earthed system that consists of a transmission line that is connected to several parallel cables, 10 km from the HV to MV busbar is considered. Figure 9.10 shows the maximum earth fault current of the system if the length of each cable is 10 km and number of parallel cables is varied between one and eight. The figure shows the maximum earth fault current if the transmission line that connects the parallel cables to the busbar is underground cable, as well as if the 10 km transmission line consists of overhead line.

As expected, the simulated earth fault current is larger than the corresponding current in a system in with strictly parallel feeders connected at the busbar, but smaller than the earth fault current in a system of the same total length consisting of longer feeders. The use of overhead line for the first 10 km reduces the current slightly, compared to cable use. This is because the zero sequence series resistance of the cable is larger than the corresponding overhead line parameter.

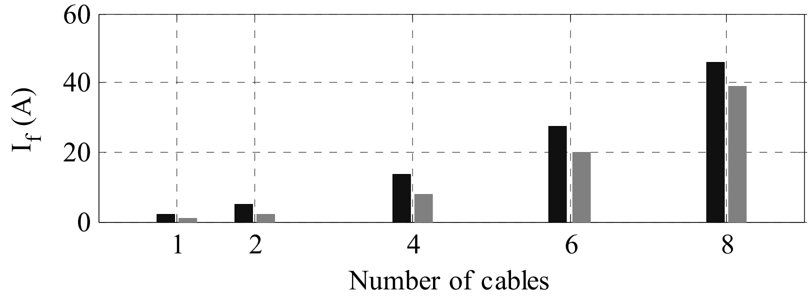

Figure 9.10 Earth fault current contribution of a 10 km cable (black) or overhead line (grey) that is connected with up to eight cables, each 10 km. The Petersen coil losses are 2 %.

Figure 9.11shows the earth fault current contribution if the parallel cables are instead connected three km from the busbar.

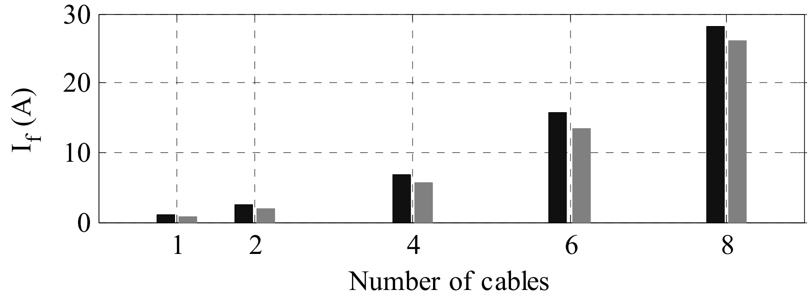

Figure 9.11 Earth fault current contribution of a 3 km cable (black) or overhead line (grey) that is connected with up to six cables, each 10 km. The Petersen coil losses are 2 %.

The series impedance of the 3 km transmission line is considerable smaller than that of the 10 km transmission line. Consequently, the equivalent resulting resistance and the magnitude of the earth fault current is also small compared to that in Figure 9.10.

The maximum inductive current generated in the central Petersen coil, in case of eight parallel cables is approximately 170 A.

Chapter 10

Conclusions

This work explains why the earth fault behaviour of electric distribution systems consisting of few long cables is different from that of conventional systems consisting of many short cable feeders. The thesis is intended to be a tool for operators to design their own guidelines, based on cable parameters, maximum earth fault currents and relay thresholds specified for their distribution systems.

If the sequence parameters of the network components are known, or can be accurately approximated, the fundamental frequency earth fault behaviour of almost any distribution network can be analysed by use of either circuit analysis or time simulations. As seen in this work, results obtained from the circuit analysis are in accordance with the results obtained from time simulations. The accuracy of the results depends on the level of details in the models.

In terms of equivalent impedance and earth fault behaviour, the main difference between the new rural cable distribution systems and conventional urban cable distribution systems is that the zero sequence series impedance of the rural systems is not necessary negligible. The zero sequence series impedance consists of a resistive as well as an inductive part, and consequently the equivalent impedance has a resistive component that cannot be compensated for by use of Petersen coils.

This work shows that the zero sequence series impedance reaches non-negligible values in strictly radial cable feeders that are very long (approximately exceeding 30 or 40 km). The author is not aware of any cables feeders of this length yet in operation in Swedish distribution systems. It is however possible that overhead feeders of this length will be replaced by underground cables in the ongoing process of increasing the reliability of the Swedish rural electrical distribution systems.

Further, the work shows that the zero sequence series impedance of branched cable systems consisting of considerable shorter cables connected to several parallel feeders a distance from the feeding busbar, is not necessarily negligible either. This kind of system is already a reality in Swedish electrical distribution systems.

10.1 Summary of results

The earth fault behaviour of electrical distribution systems with long cables is different from that of systems with short cables, even if the total cable length is the same. One long cable feeders can be seen as the series connection of n short cable segments. The relation between the series impedance and the capacitive shunt impedance is thereby in the order of n^2 compared to that of one short cable segment. Consequently, the series impedance of long cable feeders is not necessarily negligible. The relation between series impedance and capacitive shunt impedance of branched cable feeders is also large compared to that of a single short cable segment and hence, the series impedance cannot necessarily be neglected.

If the zero sequence series impedance is not negligible, the equivalent zero sequence impedance of the system has a resistive part. This resistive component cannot be compensated for by use of conventional resonance earthing. The equivalent zero sequence resistance damps the resonance of the system and by that influences the earth fault behaviour. During low-impedance faults, the damping will result in a relatively large resistive fault current that might be a threat to safety aspects in the system. During high-impedance faults, damping decreases the neutral point displacement voltage and by that, makes fault detection difficult. In addition, the series impedance will also give rise to voltage drops along the transmission line so that the zero sequence voltage is not equal all over the system.

The zero sequence series resistance, series impedance and shunt capacitance of cables are much different from those of overhead lines. The electrical zero sequence wavelength of cables is therefore much shorter compared to that of overhead lines. Resonance and non-linear behaviour do therefore occur for considerable shorter cables than overhead lines. The minimum fundamental frequency resonance length of underground cables is approximately 120 or 130 km. This can be compared the approximate minimum resonance length for overhead lines, which is to 1000 km. Combinations of inductive overhead lines and capacitive cables might also lead to series resonance and high resistive earth fault currents.

The influence of the zero sequence series impedance on the equivalent impedance of the system differs depending on the location of the fault. The earth fault behaviour during low-impedance faults is therefore different for different fault locations. In case of high-impedance faults, the difference due to fault location is small compared to the fault resistance and does not considerably influence the system behaviour. Since the fault location influences the equivalent capacitance of the system, the Petersen coil can not be tuned to compensate to the same degree, independent on fault location.

The voltage drop across the zero sequence impedance of the transformer further decrease the neutral point displacement voltage so that the current generated in the Petersen coil might not be sufficient to compensate for the capacitive earth fault current of the system. Since the zero sequence impedance of small transformers in general is larger than that of large transformers, this might set a limit for the minimum size of the transformers in electric distribution systems with extensive use of cables.

The zero sequence series impedance influences the fault behaviour of systems with long cables and it is therefore of importance to find correct values for these parameters. The zero sequence parameters of underground cables depend on cables properties such as conductor and screen area, as well as the installation. One important finding of this work is that the zero sequence impedance is not necessarily proportional to the cable length.

Distributed compensation increases the shunt impedance of underground cables so that the influence of the series impedance decreases. If the local compensation coils are accurately dimensioned, the impact of the series impedance is drastically reduced and the series impedance contributes less to the equivalent system resistance and resonance damping. There are resistive losses in the local Petersen coil, which to some extent damp the resonance. The equivalent zero sequence resistance is however considerable smaller than that of in systems with conventional, central compensation.

10.2 Future work

The work presented in this thesis concerns fundamental frequency behaviour but earth faults in cables systems are also associated to transient fault behaviour. Several aspects, such as personal safety and fault detection of long cable systems might be influenced by charge and discharge transients as well as harmonics originated from other sources. It is also of interest to consider intermittent earth faults in cable systems.

The accuracy of the results of the earth fault analysis depends on the modelled components. To increase the reliability of the results, the high voltage network, voltage source and transformers, as well as the low voltage network and loads can be modelled in more detail. It could also be of interest to study how long MV cables influence the LV and HV system fault behaviour.

Measurements are of considerable importance to evaluate the obtained results. Measurements on installed cables are also necessary to gain more knowledge about the zero sequence series impedance of underground cables.

Finally, it might be worth to study alternative compensation methods and consider the possibility to introduce other distribution system earthing designs, such as solid earthing.

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