Improving High Voltage Power System Performance Using Arc Suppression Coils

by

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ABSTRACT

Arc suppression coils provide a low cost method of increasing both the reliability and safety of high voltage transmission and distribution systems. Although the concept is not new, the advent of modern control equipment allows fresh opportunities for them to be used to save lives and to decrease the cost and inconvenience to industry and the community in general that is caused by electricity supply interruptions without incurring large expenditure. Earth fault currents are reduced to almost zero, thus eliminating many short time power supply interruptions and preventing damage to the electricity supply system at the time of the initial fault. Because of the reduction in damage at the time of the fault, many longer duration interruptions are avoided. It is common for live high voltage conductors to be close to the ground and for the fault not to be detected by conventional power system protection equipment. Arc suppression coil systems can detect high impedance earth faults and broken conductors which cannot be detected by conventional protection systems.

There are many system abnormalities which can cause neutral voltages in arc suppression coil systems. The appropriate action to be taken by the protection system depends on the type of system abnormality. The causes of neutral voltages in arc suppression coil systems are analysed and criteria are developed to differentiate between them based on the phase angle and magnitude of the neutral voltage. Fully computerised power system protection systems are now being implemented. These modern protection systems will be able to utilise the criteria developed in this research to take immediate appropriate action based on the neutral voltage caused by the system abnormality.

In existing distribution systems there is a widespread use of two single phase pole mounted auto-transformers connected in open-delta configuration to provide economic in-line three phase voltage regulation. An original method of representing open delta regulators in symmetrical component analyses is developed. It is shown that when open-delta regulators are used in a power system equipped with an arc suppression coil very high voltages can occur. A solution is proposed whereby three single phase pole mounted auto-transformers connected in a closed-delta arrangement are used.

One of the potential problems with these systems is cross country faults caused by the neutral voltage displacement combined with the transient voltages at the time of the initial earth fault. These transient over-voltages are analysed in detail and a method of testing the capability of existing system components to withstand the over-voltages is developed. Simple methods to estimate the transient voltages on overhead power systems are derived. A new method of minimising the transient over-voltages is proposed.

CERTIFICATION OF DISSERTATION

I certify that the ideas, experimental work, results, analyses, software and conclusions reported in this dissertation are entirely my own effort except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award except where otherwise acknowledged.

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Signature of Candidate	Date

ENDORSEMENT

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Signatures of Supervisors	Date

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Ergon Energy staff provided access to the high voltage testing facility and invaluable assistance with the high voltage tests.

My wife, Margaret, endured my seemingly endless time engrossed in the work. She supported and encouraged me. She helped with the proof reading of this dissertation.

CONTENTS

LIST OF FIGURES

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PUBLICATIONS

The following papers are direct outcomes of this research project.

Published

[1] R. Burgess and A. Ahfock, "The use of arc-suppression coils in power systems with open-delta regulators," in *Universities Power Engineering Conference (AUPEC), 2010 20th Australasian*, pp. 1-6.

[2] R. Burgess and A. Ahfock, "Minimising the risk of cross-country faults in systems using arc suppression coils," *Generation, Transmission & Distribution, IET,* vol. 5, pp. 703-711.

[3] R. Burgess and A. Ahfock, "The use of voltage regulators in power systems with arc-suppression coils," in *Universities Power Engineering Conference (AUPEC), 2011 21st Australasian*

Under consideration for publication

[4] R. Burgess and A. Ahfock, "Evaluation of neutral voltages in arc suppression coil systems".

Chapter 1 JUSTIFICATION FOR THE PROJECT

1.1 Principle of operation of arc suppression coils

Arc suppression coil systems are based on the Petersen coil principle that was invented in 1917 [1]. The high voltage system supply point neutrals are earthed through inductors which are tuned to the total line to earth capacitance of the system. When an earth fault occurs there is very little voltage on the faulted phase line and the voltages on the other phases and the neutral are displaced accordingly. This results in the normal line to line voltage being applied between the two healthy phase lines and earth for the duration of the fault. If the inductor is properly tuned the capacitive current resulting from the voltage displacement is equal and opposite to the current in the earthing inductor. The residual fault current will be very small and will not be sufficient to maintain an arc. There is therefore no arc or thermal damage at the point of the fault and many faults self extinguish. This can result in a significant increase in system performance [2, 3]. Many high impedance line to earth faults cannot be detected by conventional power system protection schemes. In arc suppression coil systems a high impedance line to earth fault will cause a rise in the neutral voltage. By monitoring the neutral voltage these high impedance faults can be detected. This can greatly improve the system safety.

1.2 Reasons for using arc suppression coils

Reliability of electricity supply especially in rural areas is now becoming an important issue because of the greater dependence on computers, internet access and general electrical equipment.

Arc suppression coil systems can greatly improve the reliability of supply for two main reasons.

1. Many faults on overhead high voltage distribution systems are single line to earth faults. In a large proportion of these cases, once the power supply has been interrupted it can immediately be restored successfully. These faults include lightning flash over with power follow current, conductors clashing in high wind, branches falling on the lines without breaking them, and so on. Restoration is currently achieved using automatic reclosing of circuit breakers within about 5 seconds. These short duration outages are very inconvenient for many users. Most personal computers shut down and lose data. Electric clocks need to be reset. Many industrial processes are disrupted and considerable work time is required to enable them to be restarted. With an arc suppression coil in use, these short time power interruptions caused by single line to earth faults are avoided and the supply of power continues uninterrupted during the fault.

2. Many of the line to earth faults develop into permanent faults because of the damage caused by the fault current. These include distribution transformer fuses being blown by power arc current following lightning flashover and conductors being heated to the extent that they part under the normal line tension, and so on. These faults are avoided when an arc suppression coil system is installed because there is no significant fault current. There is a corresponding decrease in the cost of power system emergency repairs.

The community is regarding electricity safety as being of increasing importance because of a decreasing acceptance of accidental serious injury and death together with a greater reliance on the convenience of electrical appliances. Many situations where a live high voltage overhead conductor has come within reach of people on the earth cannot be detected by conventional protection systems that depend on a significant flow of current to earth. A large proportion of these faults can be detected in power systems incorporating arc suppression coils because there is a neutral voltage present for most broken conductor or high earth fault impedance faults.

In response to a large loss of life and property in Victoria, Australia, in February 2009, caused by bushfires that were allegedly started by high voltage power line faults, the Victorian government has amended the relevant acts of parliament to mitigate the risks of bushfires being started by electric lines. As reported in [4], part of the Victorian government’s submission to the Victorian Bushfires Royal Commission included a recommendation for changes to power lines and distribution feeders which include “current and emerging methods of fault detection and fault level reduction’. Arc suppression coils improve fault detection and also reduce fault levels.

1.3 Current Usage of arc suppression coils

Although the concept of arc suppression coils is not new there is renewed interest in them as a result of the increased emphasis on safety and reliability together with some of the enhancements now possible because of the use of solid state technology. Arc suppression coil systems have been used in some parts of continental Europe, but they have had very limited use in other places. The writer has personal experience of an arc suppression coil installation in a 66 kV sub-transmission system in Queensland, Australia, being permanently taken out of service because of the incidence of cross-country faults.

In Australia there is currently only one arc suppression coil installed in Victoria on a trial basis. It is vital that trial installations are such that all of the potential problems and advantages are properly understood so that the trials will be successful and full installations can proceed in an effective manner.

1.4 Aim of the research

The aim of the research is to improve both reliability and safety of the power supply systems by enhancing the prospect of a wider application of the arc suppression coils. This involves;

a) Developing new ways for modern automatic protection systems to be programmed to take the appropriate action depending on the nature of the fault so as to gain further benefit from the installation of arc suppression coil systems.

b) Identifying various obstacles to the successful implementation of arc suppression coils systems and providing power system designers with practical tools and suggestions to design arc suppression coil systems which will operate successfully.

1.4.1 Analysis of neutral voltages and appropriate responses.

Objective 1 - Evaluate the causes of a sudden increase in the neutral voltage in high voltage systems fitted with arc suppression coils and show how this information can be used to facilitate appropriate action by the automatic high voltage protection systems.

There are several types of abnormal power system conditions which can give rise to a sudden increase in the power system neutral voltage. It is shown that, in general, the type of abnormal system condition can be identified by the magnitude and the phase angle of the neutral voltage. By using the criteria developed in this research, power system protection engineers will be able to design the automatic protection systems to monitor the neutral voltage and to take appropriate action immediately.

1.4.2 In-line single phase voltage regulators

Objective 2 - Evaluate the likely over-voltages on high voltage distribution systems fitted with arc suppression coils when open delta connected single phase auto-transformers are used to provide in-line voltage regulation and seek an economic alternate method of providing in-line voltage regulation.

One of the difficulties to be overcome when installing arc suppression coils in rural high voltage distribution systems is the issues which arise with in-line auto-transformer voltage regulation.

The use of two auto-transformers connected in open-delta to regulate the voltage in three phase high voltage distribution systems, as shown in Figure 1.1, has now become common practice because of cost savings.

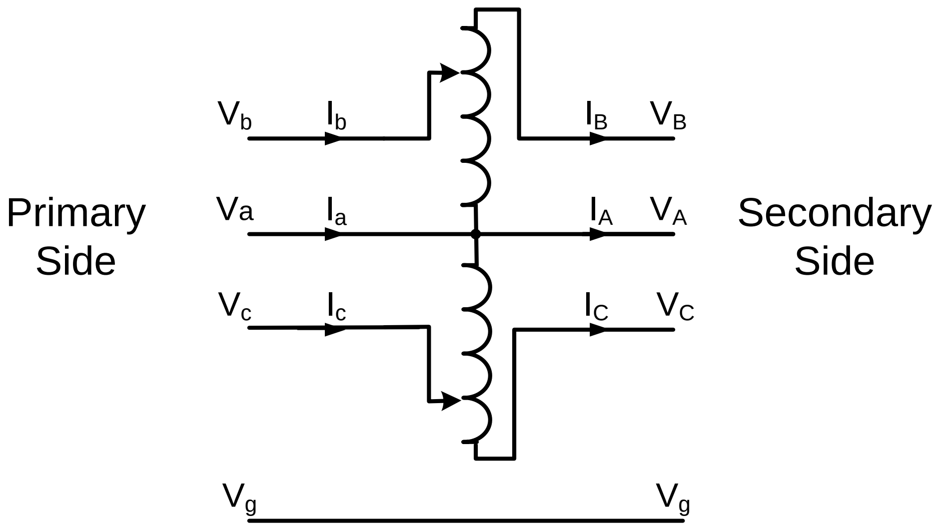


Figure 1.1 Connection diagram of a high voltage open-delta voltage regulator.

Open-delta voltage regulators increase the line to earth voltage in two phases only. Because the line to earth voltages are no longer equal in magnitude, the line to earth capacitance currents will no longer add to zero. Current will therefore flow through the earthing inductor. As the inductance of the earthing coil is cancelled by the line to earth capacitances, the magnitude of current will only be limited by the resistance in the circuit and saturation of the magnetic core of the earthing inductor. This can result in excessive neutral voltage displacement and corresponding over-voltages in one or more of the phases. Depending on the system configuration the voltages can be high enough to cause insulation failures.

The older, more expensive, three phase auto-transformers cannot be used without impairing the effectiveness of the arc suppression coil system. Various options for providing in-line voltage regulation are analysed and a solution is proposed.

1.4.3 Minimising cross-country faults caused by voltage transients

Objective 3. - Research the causes of cross-country faults in high voltage power systems fitted with arc suppression coil systems and seek methods of reducing the incidence of them.

Cross-country faults have previously prevented the successful implementation of arc suppression coil systems. When a single phase line to earth fault occurs in a power supply system fitted with an arc suppression coil, the insulation on the other two phase lines is stressed. Typical voltages before and after a single phase to earth fault in an 11 kV distribution system with an arc suppression coil, as simulated mathematically, are shown in Figure 1.2.

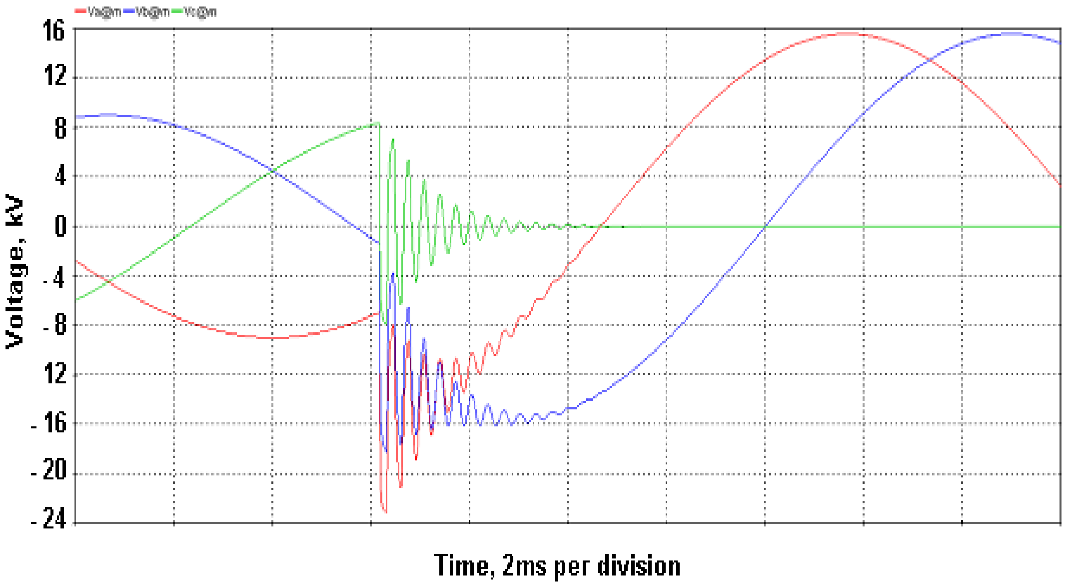


Figure 1.2 Typical line voltages before and after a single phase to earth fault on an 11 kV distribution system fitted with an arc suppression coil.

If a second earth fault occurs on another phase line there are then two faults usually on remote parts of the system. This is a phase to phase to earth fault. The earth component can be neutralised by the arc suppression coil but the line to line component of the fault cannot be neutralised. There are then two parts of the system affected by faults and the situation is worse than it would have been if an arc suppression coil had not been installed.

A previous installation of an arc suppression coil system in Queensland, Australia was permanently taken out of service because of simultaneous faults caused by the increased voltage on the two healthy phase lines, together with transient voltages, at the time of the fault.

The characteristics of high transient voltages caused by the occurrence of line to earth fault in power systems with arc suppression coils are analysed. Simple techniques for estimating the likely maximum transient voltages are provided. A method of assessing the ability of the existing line insulation to withstand the high transient voltages is developed. A means of reducing the peak transient voltages is proposed.

1.5 Outline of dissertation

1.5.1 Analysis of neutral voltages

The neutral voltages which occur when a fault occurs in a power system fitted with an arc suppression coil are analysed in detail to find out whether the neutral voltage phase magnitude and phase angle can provide sufficient information for computerised automatic protection systems to take appropriate action depending on the fault type.

1.5.2 In-line single phase voltage regulators

The over voltages that can occur during normal operation when two single phase auto-transformers connected in open-delta are used in a power system fitted with an arc suppression coil are analysed in detail and other methods of using single phase auto-transformers to provide in-line voltage regulation are assessed.

1.5.3 Minimising cross-country faults caused by voltage transients

The high transient voltages which can occur when a fault occurs in a power system fitted with an arc suppression coil are analysed in detail. Methods of reducing the cross-country faults caused by these transient voltages are proposed.

1.6 Summary of research outcomes

1.6.1 Analysis of neutral voltages

It is shown that, for power systems fitted with an arc suppression coil, the type of fault can be determined by monitoring the neutral voltage magnitude and phase angle. On the basis of this information, computerised protection systems can be programmed to take appropriate action automatically. A possible logic sequence for the automatic operation is proposed.

1.6.2 In-line single phase voltage regulators

It is shown that neither open-delta nor star connected auto-transformers should be used to provide in-line voltage regulation in a power system fitted with an arc suppression coil. The use of three single phase auto-transformers connected in delta is proposed.

1.6.3 Minimising cross-country faults caused by voltage transients

Simple methods of estimating the transient over voltages are provided. A simple method of testing the capability of existing system components ability to withstand the transient over voltages is shown. Equipment to reduce the magnitude of the over-voltages is proposed.

Chapter 2 LITERATURE REVIEW AND SCOPE

The principle of arc suppression coils has been known since 1917 [5]. Improvements in system performance with the use of the system have been documented [3, 4].

2.1 Usage of arc suppression coils

Experience in the United States of America in the 1930s was that arc suppression coils could improve the performance of the transmission system[6]. It is reported in [7] that as the transmission system grew the expense of upgrading the arc suppression coil systems was not warranted because more duplicate supplies were available.

As set out in [8], the reasons arc suppression coils have not been more widely used in Continental Europe include;

- The reliability and sensitivity of conventional protection systems is decreased.
- Permanent faults are more difficult to locate.
- There is a need for a higher level of insulation.
- There will be more cross-country faults.

Although arc suppression coils have had limited use there is now renewed interest. The availability of digital control, high voltage thyristors and other power electronic devices has led to the development of automatic tuning systems to ensure that the residual fault current is minimised [9-17]. Swedish Neutral AB have developed a scheme whereby a current is injected into the neutral to neutralise any remaining earth fault current [18]. A method of automatically determining the system parameters by injecting current into the transformer neutral at two different frequencies has been proposed [19]. Over-voltages during a fault caused by zero sequence line inductance in series with line capacitance has been analysed [20]. There have also been significant developments in methods to locate a permanent fault [21-30]. A method of minimising the effect transient DC offset currents have on the extinction of the arc has also been proposed, whereby the neutral is left unearthed and the arc suppression coil is then switched in at the time of the first neutral voltage peak after the fault [31]. This method will reduce the sensitivity of the system to high impedance faults. A method of identifying the system parameters by evaluating the records of actual system faults has been proposed [32]. The phenomenon of high voltages as a result of unequal capacitances to earth has been investigated [33, 34] and a compensation mode to reduce the voltage levels has been proposed[35].

2.2 Analysis of neutral voltages

Two common fault types which cannot easily be detected using conventional methods are:

1. High impedance earth faults, and

2. An open circuit in a conductor.

Arc suppression coil systems can detect high impedance faults because it takes only a small earth current to cause a voltage to appear across the tuned arc suppression coil. There has been recent work on detecting and locating high impedance faults. A means of detecting high impedance faults in unearthed and compensated systems by analysing transient fault currents has been proposed [36]. A method of detecting high impedance faults using distance relays has also been proposed but the method depends on having relays at each end of the line [37].

There has been considerable work on methods of detecting the faulty feeder when there is a permanent earth fault, but detecting the faulty feeder when there is an open circuit is not mentioned [21, 23-25, 28-30, 38, 39]. Methods of detecting these types of faults using the significant load currents have been investigated[40, 41]. When the line is part of a ring system an open circuit can be detected by comparing load currents as in [42].

The human safety aspects of speed and sensitivity in detecting and clearing earth faults have been analysed and are well documented [43].

None of the previous work provides a means of detecting the dangerous situation of a broken overhead conductor in a lightly loaded radial feeder with the load side end on the earth or a broken end not making contact with the earth. A common dangerous situation is where a motor vehicle collides with a pole and a broken conductor end rests on the top of the vehicle but is insulated from the earth by the vehicle tyres. In at least one case, an open circuit with no earth fault was wrongly diagnosed as a permanent earth fault and resulted in considerable damage to 132 kV equipment before the fault was isolated [33].

It is shown in this dissertation that it is possible to differentiate between most of the various types of faults by monitoring the neutral voltage magnitude and phase angle. In particular, in the case of a broken conductor it is possible to detect the fault when there is only a small amount of load past the fault point. The amount of load required depends on the total system parameters. This phenomenon is fully analysed to determine the effectiveness of arc suppression coil systems in mitigating this risk to the public. Criteria are developed to determine the type of fault in many cases.

It is envisaged that future power system protection will be based on the widespread computerised control of the system or substation using methods such as that being implemented in The Netherlands that is described in [44-46] rather than on individual protection relays. These protection systems will facilitate intelligent decision making which may utilise the measured magnitude and phase angle of the neutral voltage as proposed in this dissertation.

2.3 In-line single phase voltage regulators

Using two single phase regulators connected in open-delta provides an economical means of in-line voltage regulation in high voltage distribution lines.

Previous detailed analyses of open-delta voltage regulators provide a base for further work [47-49]. The phenomena of neutral voltages as a result of the use of open-delta connected single phase voltage regulators in power systems with arc suppression coils has been recognised [50]. However none of this previous work used symmetrical components in the analysis. The interaction between neutral voltages and earth currents in complex three phase power systems can best be understood and evaluated by using symmetrical components. Many modern protection systems use zero sequence current measurements as one of the criteria for correct operation. A search of the published literature did not find a method of representing open-delta voltage regulators using symmetrical components. A model to represent open-delta voltage regulators using symmetrical components is developed. This model is then used to evaluate the over-voltages that can occur when arc suppression coil systems are used in conjunction with open-delta voltage regulators. Although arc suppression coils have been in use for many years, the widespread use of open-delta voltage regulators is relatively new. There does not appear to be significant experience in the use of both on the same distribution system. In particular, no quantitative analysis of the use of open-delta voltage regulators and arc suppression coils in the same high voltage power system has been reported.

Methods of providing in-line voltage regulation in power systems fitted with arc suppression coils are analysed and a solution is proposed.

2.4 Minimising Cross Country Faults

The phenomenon of transient voltages resulting from a single line to earth fault adding to the increased line to earth voltages and thus increasing the strain on the insulation of the other two phase lines has long been recognized [51].

Experience has shown that there is likely to be an increased incidence of simultaneous faults when arc suppression coil systems are used [52-54]. The transient voltages are the result of high frequency voltage and current oscillations. To calculate the magnitude and frequency of the voltages it is necessary to allow for the skin effect on the line resistance and inductance parameters. The method proposed by Gatous and Pissolato [55] to allow for the skin effect and the well known complex depth of return method as reiterated by Wang and Liu [56] are useful for calculating the zero sequence line parameters. The work by Marti [57] on modelling transients oscillations using frequency dependent parameters is the basis for the ElectroMagnetic Transients Program (EMTP) which is used to confirm the analytical calculations and to carry out more detailed studies of transient phenomena. EMTP is well proven commercially available software. There has been further work on transient oscillations in high voltage transmission lines but no detailed analysis on systems fitted with arc suppression coils [58-62].

The transient voltages are analysed in detail and strategies to minimise cross country faults are proposed.

Chapter 3 METHODOLOGY

In general the adopted research method is to;

- Search the available literature for previous work that can be built on.
- Use an analytical approach to estimate the effects.
- Confirm the analytical results using commercially available power system software.
- Propose solutions or enhancements to existing systems where feasible.
- Confirm the effectiveness of the proposed solutions or enhancements using the analytical approach and commercially available software.
- Build a physical model as further confirmation of the results where feasible.

3.1 Analysis of neutral voltages

Properly tuned arc suppression coil systems are very sensitive to high impedance earth faults. In the case of a broken conductor with the load side on the earth the limiting factors in detecting a fault are the earth fault impedance and the impedance between the healthy conductors and the faulted conductor on the load side. That impedance between the healthy conductors and the faulted conductor on the load side is determined not only by the actual load connected at the time, but also by the no-load impedance of the transformers connected on the load side. An analytical approach is utilised to determine the detection limits in terms of the transformer no load impedances, the load connected and the fault impedance. The calculations are then confirmed using the ElectroMagnetic Transients Program (EMTP) software.

One possible logic diagram for automatic protection operation is developed.

3.2 In-line single phase voltage regulators

A means of representing an open-delta regulator using symmetrical components is derived to analyse the neutral voltages and currents when an open-delta regulator is used in a system earthed through an arc suppression coil. This representation is then used to calculate the resultant voltages. The results are confirmed using EMTP software. It is found that severe over-voltages can occur when there is no fault if open-delta regulators were to be used in power systems fitted with arc suppression coils.

The use of three star connected auto-transformers is investigated. It is determined that this is not a suitable arrangement. The arc suppression coil system would not operate correctly because of the lack of a zero sequence current path through the star connected auto-transformers arrangement.

The use of three auto-transformers connected in a closed-delta arrangement is then analysed. A method of calculating the zero sequence neutral voltage introduced if the ratios of the auto-transformers becomes out of step is derived. The calculations are confirmed using EMTP software.

3.3 Minimising cross country faults

The transient voltages and current oscillations that result when an earth fault occurs are investigated using analytical methods. These calculations are confirmed using EMPT software and a physical model. A method of reducing the transient voltages is proposed. Testing of power system components is recommended. A practical test arrangement has been trialled in a high voltage laboratory.

Chapter 4 ANALYSIS OF NEUTRAL VOLTAGES

4.1 An accurately tuned simple system

To illustrate the methods of evaluating the type of system abnormality based on the neutral voltage a simple high voltage power system, as shown in Figure 4.1, was analysed. The same principles can be applied to any practical power system.

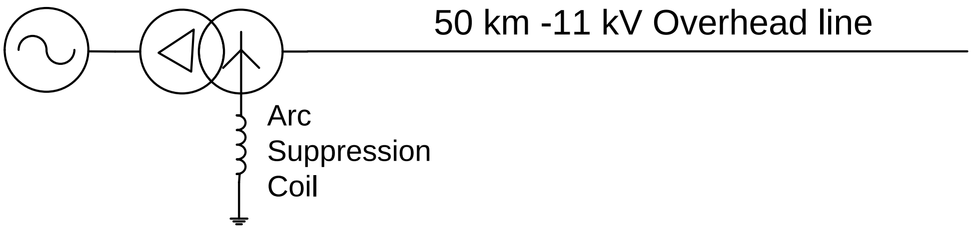


Figure 4.1 Simple single line power system.

The system simulated comprised 50 km length of typical 11 kV overhead line supplied by a transformer with a star connected secondary winding.

Although in this model a single length of line was used, the results are similar for any configuration of the network with various branches. The following realistic parameters were used for the simulations:

The positive sequence line resistance R_L^+ = 0.5 Ω per km.

The positive sequence line inductance L_L^+ = 1.75 mH per km.

The positive sequence line capacitance C_L^+ = 0.00625 uF per km.

The negative sequence line resistance R_L^- = 0.5 Ω per km.

The negative sequence line inductance L_L^- = 1.75 mH per km.

The negative sequence line capacitance C_L^- = 0.00625 uF per km.

The zero sequence line resistance R_L^0 = 0.5 Ω per km.

The zero sequence line inductance L_L^0 = 5 mH per km.

The zero sequence line capacitance C_L^0 = 0.00425 uF per km.

The positive sequence source voltage V_S^+ = 1 pu.

In accordance with the principle of operation of arc suppression coil systems, the arc suppression coil inductance, (L_C) is tuned to the total line to earth capacitance of the system as given by the equation:

$$\omega L_C = \frac{1}{3\omega C_L^0} \tag{4.1}$$

The arc suppression coil was assumed to be perfectly tuned with 2% series resistance losses and 2% magnetising losses as shown below in equations (4.2) and 4.3):

The arc suppression coil resistance $R_C = 0.02\omega L_C$ (4.2)

The arc suppression coil magnetising resistance $R_{CE} = \frac{\omega L_C}{0.02}$ (4.3)

An infinite source was assumed, as the source impedance will have minimal effect on the result. In practice the inductance of the arc suppression coil is selected so as to allow for the zero sequence inductance of the source transformer.

The well known arrangement of the symmetrical component network for a single line to earth fault is then as shown in Figure 4.2. Although the capacitances are distributed along the line, they are shown here as half at each end. This provides accurate results for short lines.

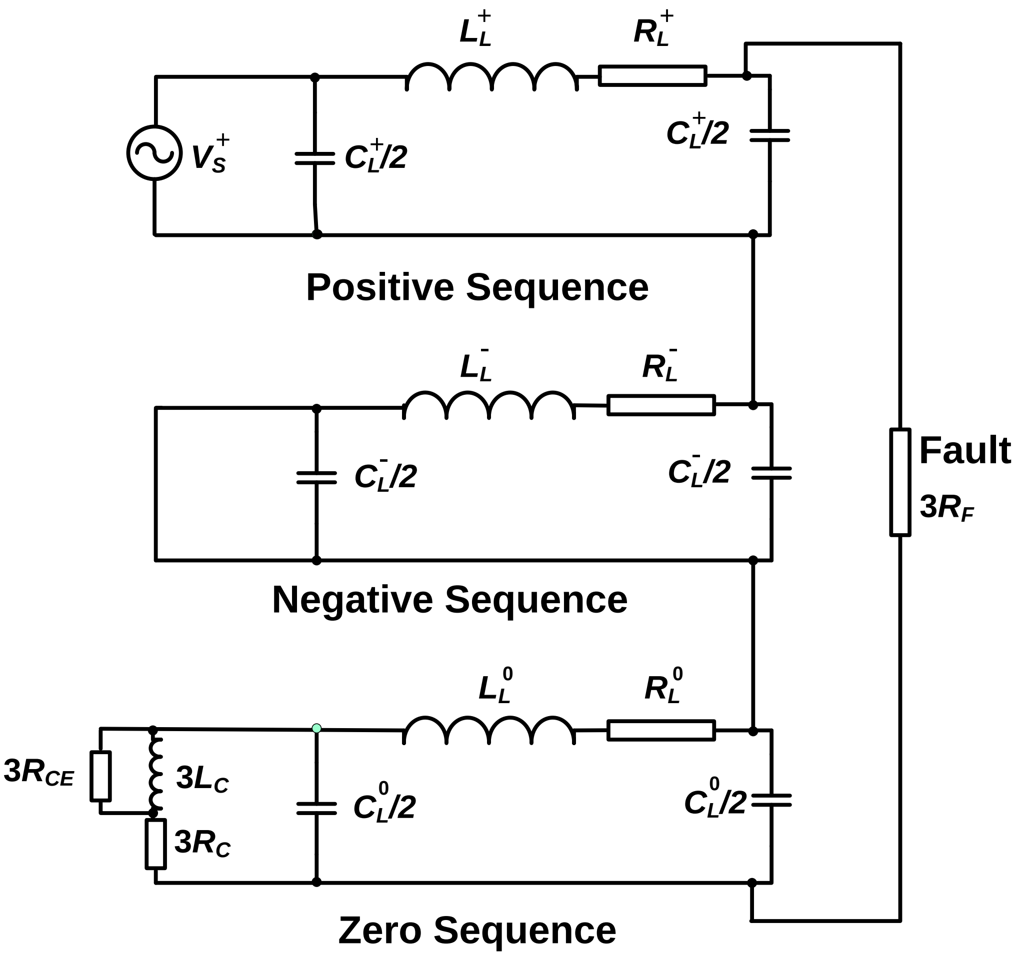


Figure 4.2 Symmetrical component network for the simple system with a single line to earth fault at the load end.

To illustrate the effect of tuning of the arc suppression coil on fault currents, the simple system was analysed for a range of values of the arc suppression coil parameters and the corresponding fault current values were plotted as shown in Figure 4.3.

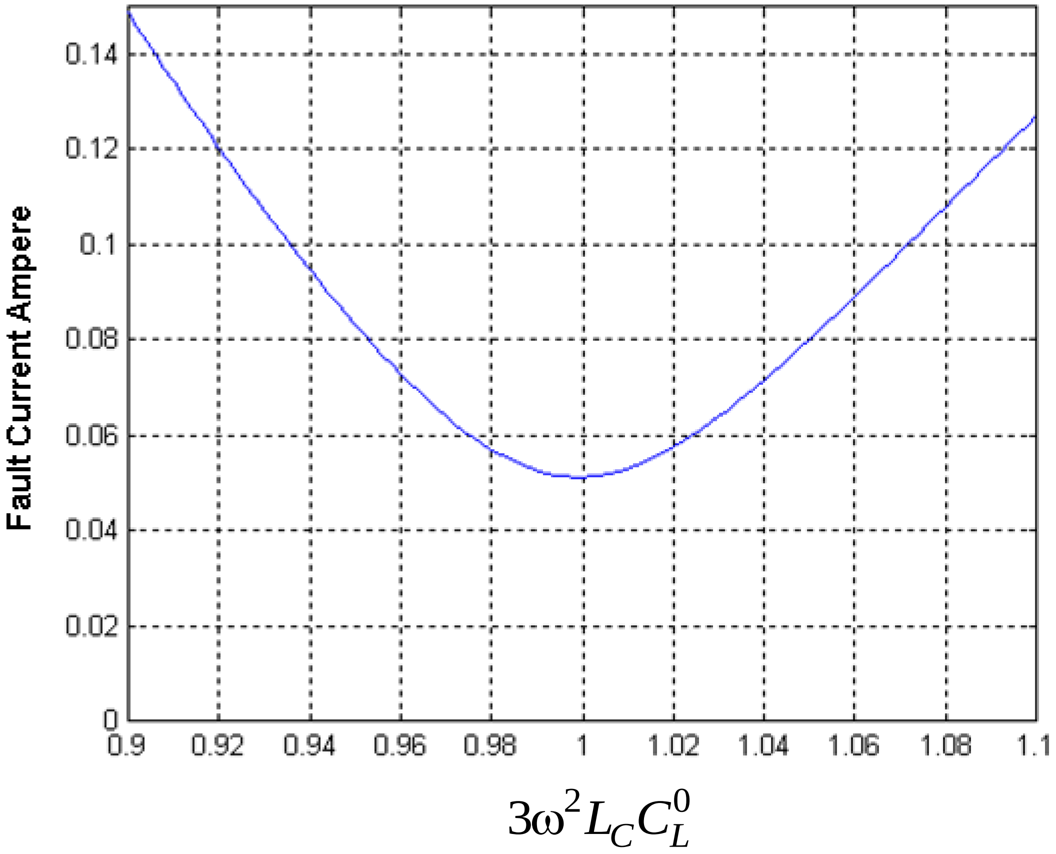


Figure 4.3 Fault currents for the simple system with a low impedance single line to earth fault and with various values of arc suppression coil parameters.

As expected, the fault current is least when the system is perfectly tuned. The value of the minimum fault current depends on the fault impedance and the equivalent series resistance of the tuned circuit. The equivalent series resistance includes the losses in the arc suppression coil, the zero sequence resistance of the source transformer as well as the zero sequence resistance of the power line.

To illustrate the effect of tuning of the arc suppression coil on the detection of high impedance faults, the simple system was analysed for a range of values of high impedance line to earth faults and arc suppression coil parameters. The corresponding neutral voltage values were plotted as shown in Figure 4.4.

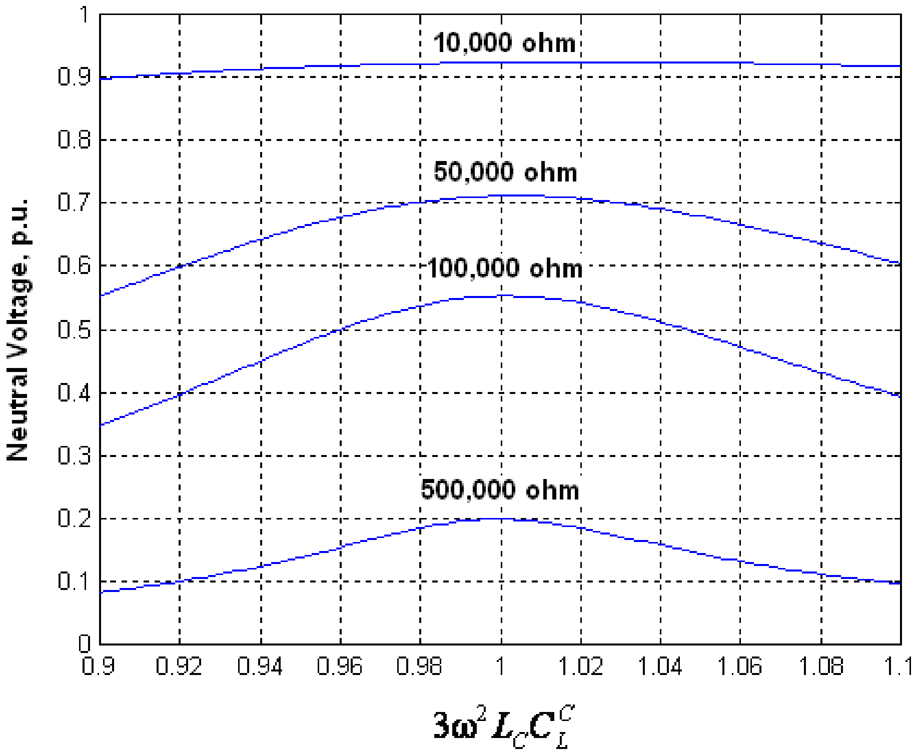


Figure 4.4 Neutral voltages for the simple system with various resistances of single line to earth faults and with various values of arc suppression coil parameters.

The curves show that faults with an impedance as high as 500,000 ohm can easily be detected by monitoring the neutral voltage. Conventional earth fault protection is limited to only detecting earth faults with impedances less than about 1,000 ohm or so. They also show that the ability of the system to detect high impedance earth faults is enhanced by keeping the system accurately tuned.

Traditionally, tuning of arc suppression coils was achieved by taps on the inductor winding. This made accurate tuning difficult to achieve. However, there have been significant developments in methods of automatically determining the system parameters [19] and automatic tuning systems [9-12]. These have become economic methods of enhancing the performance of arc suppression coil systems.

The advantages of keeping the system accurately tuned are:

- The reduced fault current will minimise the damage caused.
- The reduced fault current will increase occurrence of the extinction of the power follow arc following a lightning flash-over.
- More of the high impedance line to earth faults will be detected.

For these reasons the following analyses assume that the system is accurately tuned at the time of occurrence of the system abnormality.

4.2 Causes of abnormal neutral voltages

Three reasons for abnormal neutral voltages being generated in arc suppression coil systems that have been identified are:

- A line to earth fault
- Out of balance in the line to earth capacitance.
- An open circuit in one phase line

4.2.1 A line to earth fault.

For low impedance line to earth faults the neutral voltage will be 1.0 pu. For high impedance line to earth faults the neutral voltage will be less than 1.0 pu.

4.2.2 Out of balance in the line to earth capacitance.

An out of balance in the line to earth capacitances will cause a neutral voltage because of the out of balance capacitive current flowing through the arc suppression coil. Out of balance capacitances can be caused by the placement of conductors on the structures, by single phase spur lines, or by some sudden system abnormality. In most distribution systems it would be expected that the out of balance capacitance would be small. In transmission lines the normal phase transposition of the conductors would reduce the imbalance in the line to earth capacitance. Any sudden change in the out of balance capacitance which does not coincide with planned switching could indicate a system abnormality.

4.2.3 An open circuit in one phase line

It is shown that when there is an open circuit in one phase with significant load connected on the load side of the open circuit, the neutral voltage can exceed 1.0 pu. The lack of immediate recognition of this type of event has led to severe over-voltages and equipment damage [33].

4.3 A line to earth fault

The system as shown in Figure 4.1 was analysed, using the symmetrical component network as shown in Figure 4.2, for a range of fault resistances continuously varying from zero to 1 MΩ, and with faults on each phase line in turn. The resulting neutral voltages were plotted as shown in Figure 4.5.

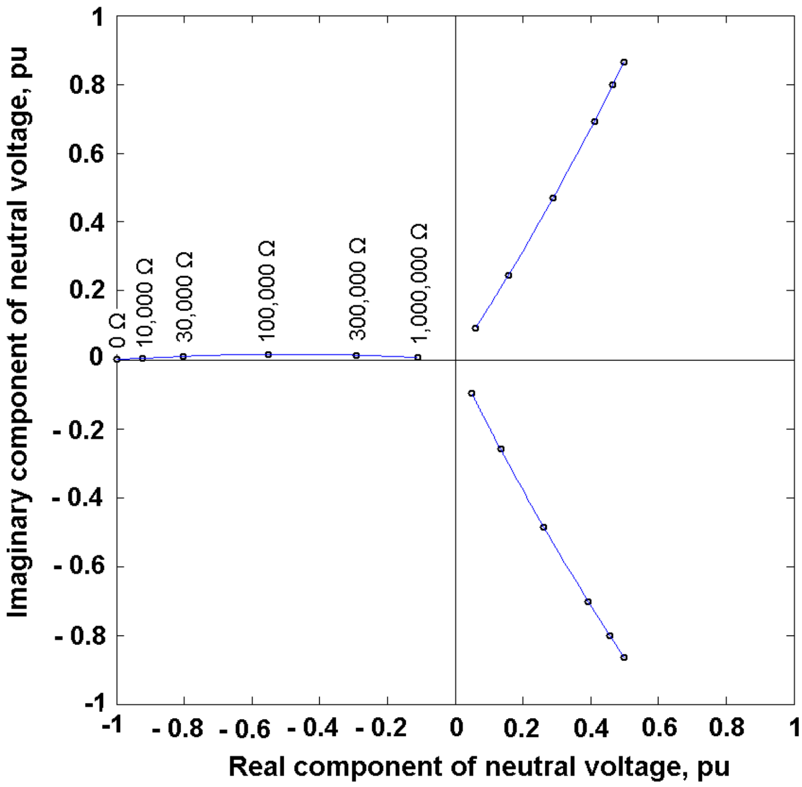


Figure 4.5 Neutral voltage for a simulated single line to earth fault varying from zero to 1 MΩ, and with faults on each phase line in turn. The reference phase angle is A to N.

The voltages for several earth fault values were checked using the ElectroMagnetic Transient Program (EMTP) software and the values were almost identical. Whereas the analysis used to derive Figure 4.5 used symmetrical components, the EMTP software does not use symmetrical component analysis.

A typical urban zone substation 11 kV network as shown in Figure 4.6 was then modelled using EMTP. As evaluated in Appendix A2, the distribution transformers connected to the system also contribute some zero sequence capacitance. A single line to earth fault was simulated on various places in the network. The results obtained with the EMTP analysis were similar to those shown in Figure 4.5.

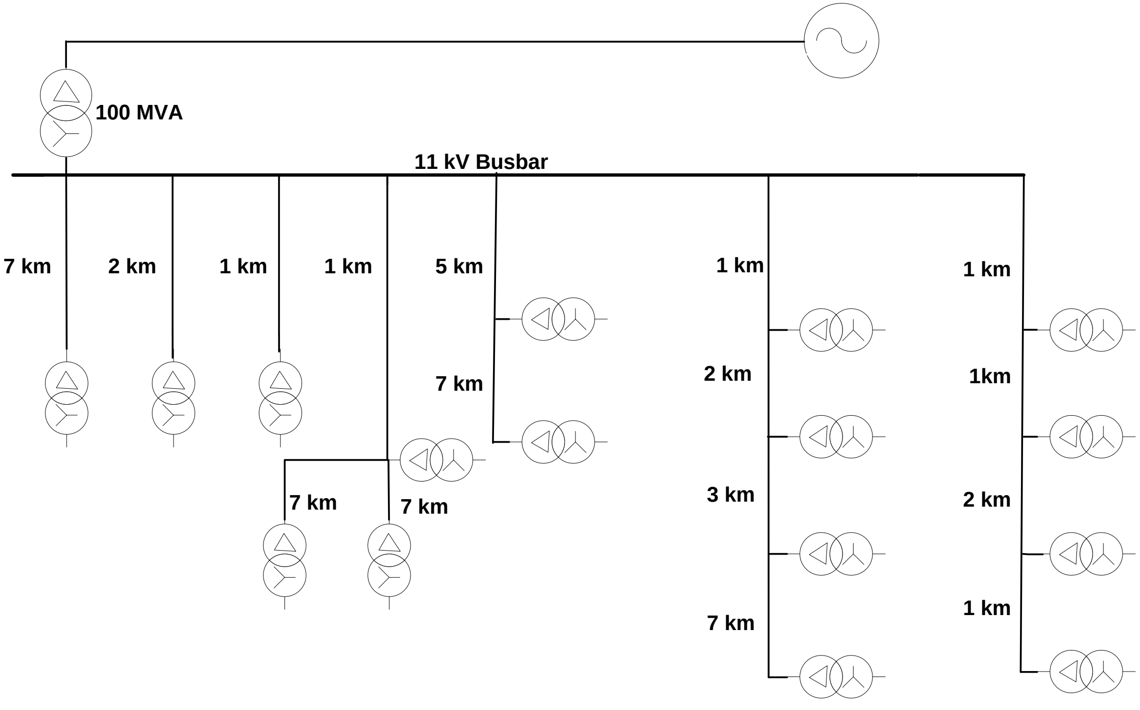


Figure 4.6 Urban Zone substation area 11 kV network.

It can be seen that the neutral voltage magnitude is never greater than 1 pu and the phase angle is close to 60^0, 180^0 or -60^0 depending on the which phase line is affected. This is to be expected as the tuned circuit with some losses would behave as a resistance. Because of the effect of the line reactance there is a small change in phase of the voltage for faults with significant impedance.

4.4 A disturbance in the line to earth capacitance balance.

As sudden system abnormalities which would cause a disturbance in the capacitance to earth balance would seem to be limited to events which would affect only a small part of the system, it is reasonable to limit the analysis to changes of up to 10%. The exception is where there are star connected capacitor banks with the star point earthed. An out of balance in delta connected capacitor banks will change the positive and negative sequence currents and voltages only.

Using the simple system shown in Figure 4.1, a change in line to earth capacitance in one phase was simulated. The symmetrical component network can then be represented as shown in Figure 4.7, where the change in line to earth capacitance in one phase is represented by ΔC^0. This is in accordance with the symmetrical component representation of an out of balance capacitance shown in [63]. An increase on the capacitance to earth in one phase would be represented by an increase in ΔC^0 and a decrease on the capacitance to earth in one phase would be represented by decrease or a negative value for ΔC^0. Where there is a decrease in the capacitance to earth in two phases the effect is represented by a decrease in the zero sequence capacitance and an increase in ΔC^0.

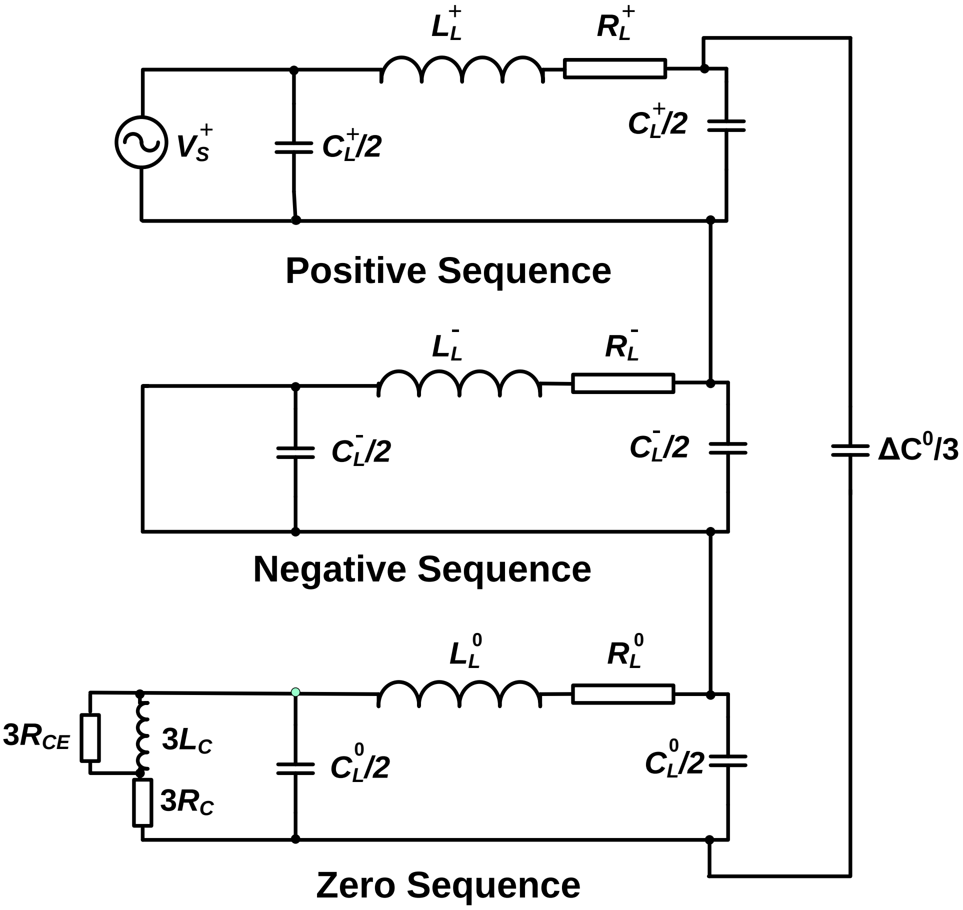


Figure 4.7 Symmetrical component network for the simple system with an out of balance line to earth capacitance.

The neutral voltage was calculated for values of ΔC^0 varying between plus and minus 10% of C_L^0. The out of balance capacitance was introduced into each phase line in turn. The resulting neutral voltages were plotted as shown in Figure 4.8.

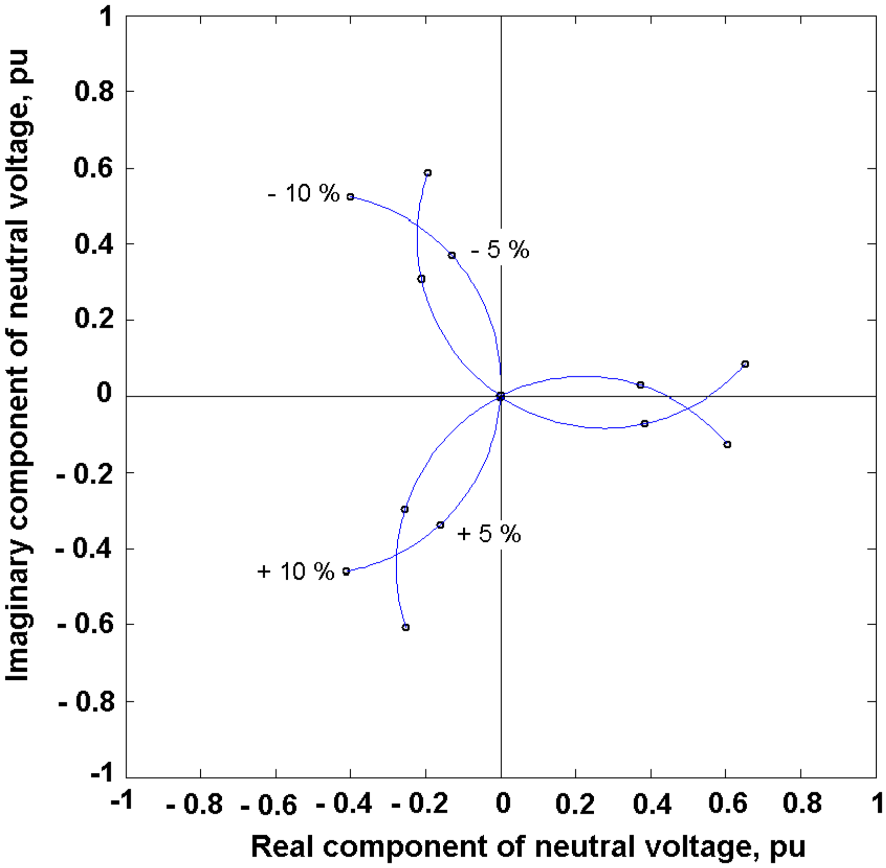


Figure 4.8 Neutral voltage for a simulated out of balance capacitance varying from plus 10% of C_L^0 to minus 10% of C_L^0 on each phase line in turn. The reference phase angle is A to N.

The voltages for several out of balance capacitance conditions were checked using the EMPT software and the resulting neutral voltages were almost identical to those shown in Figure 4.8.

Using EMTP software the out of balance capacitances were also checked for the more representative urban zone substation network shown in Figure 4.6 with out of balance capacitances introduced at various points in the system in turn. The results were similar to those shown in Figure 4.8.

It can be seen that the neutral voltage does not have a magnitude of greater than 1 p.u, and that the voltage does not have a phase angle of 60^0, 180^0 or -60^0 for any of these out of balance conditions. On the basis of the phase angle we can distinguish between an out of balance capacitance condition and a line to earth fault.

The circular shape of the plot can be understood by ignoring the line impedances and representing the arc suppression coil losses as a single resistor in parallel with the coil. The symmetrical component representation then reduces to that shown in Figure 4.9 where R_{CL} represents the arc suppression coil losses.

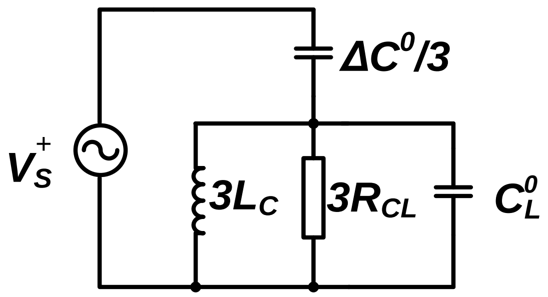


Figure 4.9 Symmetrical component network for the simple system with the line impedances ignored, the arc suppression coil losses represented by a single resistor and out of balance line to earth capacitance.

As the admittance of the coil and that of the zero sequence capacitance add to zero, we have the classic case of a capacitance in series with a resistance. The voltages across the resistor and the capacitor will always be displaced by 90^0.

The plot as ΔC^0 is varied will then be part of a circle as shown in Figure 4.10 where V_R and V_C represent the voltages across $3R_{CL}$ and $\Delta C^0/3$ respectively.

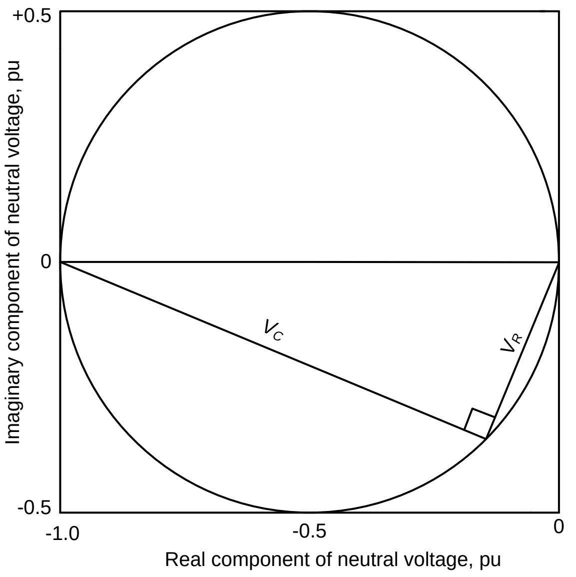


Figure 4.10 Neutral voltage for the simple system with the line impedances ignored, the arc suppression coil losses represented by a single resistor and out of balance capacitance varying from zero to infinity. The reference phase angle is A to N.

4.5 An open circuit

An open circuit can occur with or without a simultaneous earth fault. The fault could be an open circuit bridge, or it could be a broken conductor with the ends clear of the earth, insulated from the earth or in contact with the earth.

The effects of distributed generation need to be considered in many cases. Both single phase and three phase distributed generation installations are becoming more common.

4.5.1 An open circuit in one phase with no earth fault

The simple system as shown in Figure 4.1 was used to analyse the effect of an open circuit in one conductor with no earth fault.

Using the method given in [53], the system can be represented by symmetrical components, as shown in Figure 4.11, where the subscripts “M” and “N” refer to the sections of the network on the supply side and on the load side of the open circuit respectively. R_{Ld}^{+} and R_{Ld}^{-} refer the positive and negative sequence resistances representing a 100 kW delta connected load.

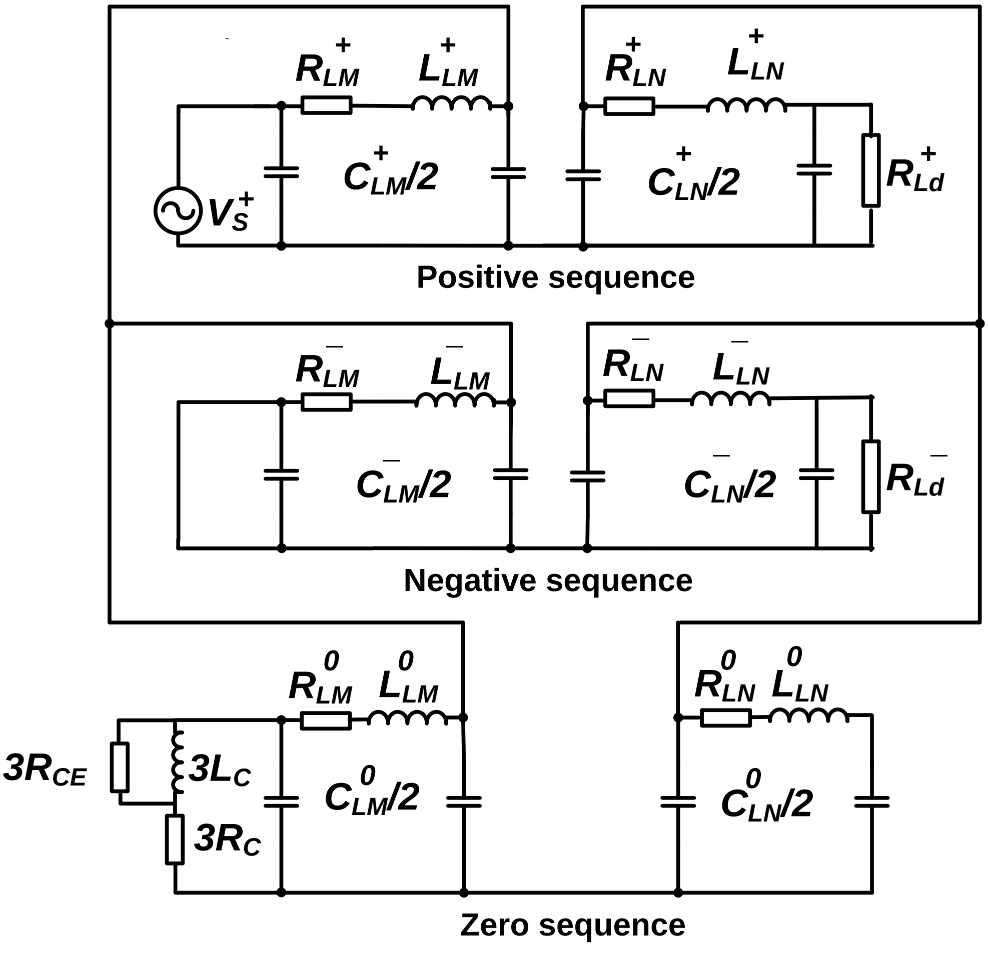


Figure 4.11 Sequence network for the simple system as shown in Figure 4.1 with an open circuit in one conductor.

This system was analysed for an open circuit with the proportion of the network on the source side of the open circuit varying continuously from 0% to 100% and on each phase line in turn. The resulting neutral voltages were plotted as shown in Figure 4.12.

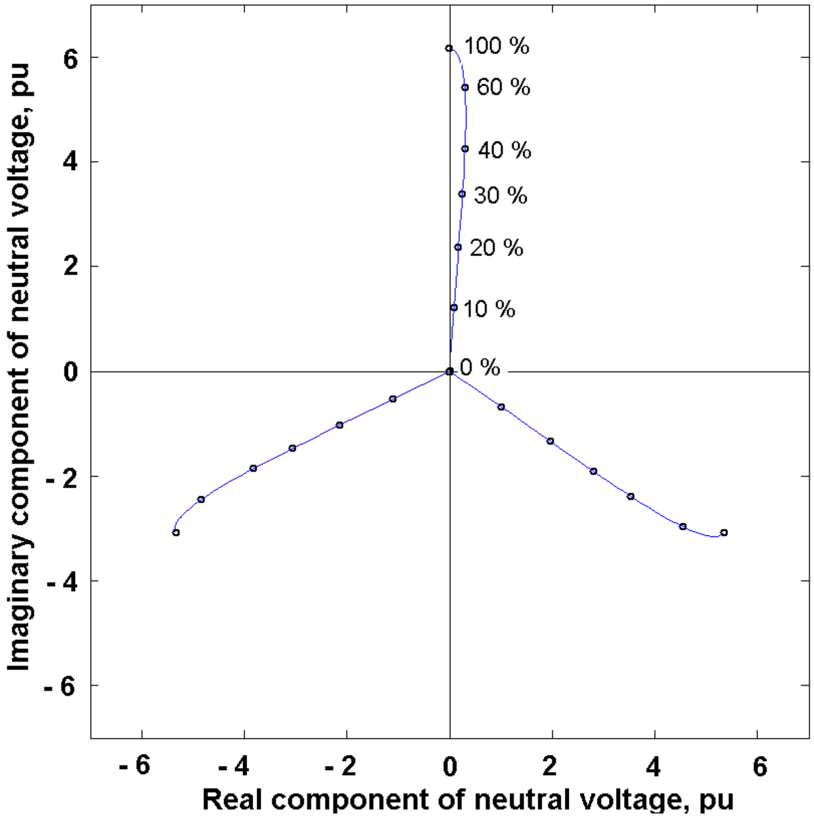


Figure 4.12 Neutral voltage for a simulated open circuit on each phase line in turn, with the proportion of the network on the load side of the open circuit varying continuously from 0% to 100% and with 100 kW of connected load on the load side. The reference phase angle is A to N.

It can be seen that depending on the position of the open circuit the neutral voltage can be higher than 1 pu. The phase angle is very close to 90^0, -150^0 or -30^0 depending on which phase line is affected.

For several values the results were confirmed with EMTP software using the both the simple system model of Figure 4.1, and an urban zone substation model, as shown in Figure 4.6.

A clearer understanding of the issue may be gained by considering a simplified system with line inductances and all losses ignored.

The sequence network then resolves to that shown in Figure 4.13.

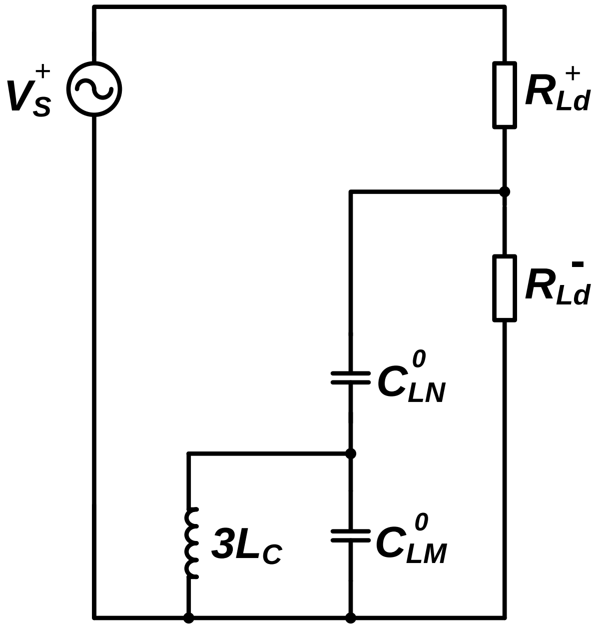


Figure 4.13 Sequence network of the simple system with an open circuit in one conductor and with line inductances and all losses ignored.

Let Y_C^0 be the zero sequence admittance of the arc suppression coil.

Let Y_{LM}^0 be the zero sequence admittance of the capacitance to earth of the network on the source side of the open circuit.

Let Y_{LN}^0 be the zero sequence admittance of the capacitance to earth of the network on the load side of open circuit.

If the arc suppression coil is correctly tuned to the line to earth capacitances then the sum of the admittances will be zero. Therefore:

$$Y_C^0 + Y_{LM}^0 + Y_{LN}^0 = 0 \tag{4.4}$$

$$Y_C^0 + Y_{LM}^0 = -Y_{LN}^0 \tag{4.5}$$

Let I^0 be the total zero sequence current. Then:

$$I^0 = \frac{V_S^+}{R_{Ld}^+ + \frac{1}{\left[\frac{1}{\left(\frac{1}{Y_C^0 + Y_{LM}^0} + \frac{1}{Y_{LN}^0} \right)} + \frac{1}{R_{Ld}^-} \right]}} \tag{4.6}$$

However the impedance of the zero sequence branch is given by:

$$Z^0 = \frac{1}{Y_C^0 + Y_{LM}^0} + \frac{1}{Y_{LN}^0} = 0 \tag{4.7}$$

Therefore R_{Ld}^- can be ignored and:

$$I^0 = \frac{V_S^+}{R_{Ld}^+} \tag{4.8}$$

The zero sequence current is limited only by the impedance of the connected load and:

$$V_n = \frac{V_S^+}{R_{Ld}^+} \left[\frac{1}{Y_C^0 + Y_{LM}^0} \right] \tag{4.9}$$

From (4.5) and (4.9) we get:

$$V_n = -\frac{V_S^+}{R_{Ld}^+ Y_{LN}^0} \tag{4.10}$$

Equation (4.10) explains the + 90^0 phase shift of the neutral voltage for an open circuit in A phase, as shown in Figure 4.12.

4.5.2 The effect of distributed generation.

In modern power systems, there are increasing numbers of distributed generation installations. Many of these use single phase inverters connected to the low voltage side of the delta-star distribution transformers. In the event of an open circuit in the high voltage network, the voltages on the load side of the two affected phase lines will be reduced to about half the normal values, as illustrated in Figure 4.14.

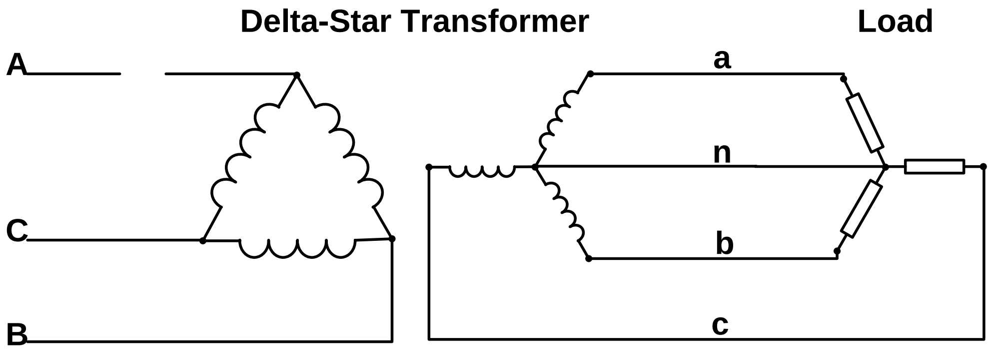


Figure 4.14 Delta-star connected transformer with an open circuit in one line.

The inverters connected to the affected low voltage phase lines will shut down on under voltage.

The remaining inverters will be injecting power in single phase mode between the two intact high voltage lines. These will not significantly affect the neutral voltage because the zero sequence network is not affected. In situations where there is three phase distributed generation, there may be a positive sequence voltage source on the load side of open circuit. As shown in Figure 4.15, and Figure 4.16, the isolated generation voltage source, V_I^+, will be in parallel with the load impedance, R_{Ld}^+.

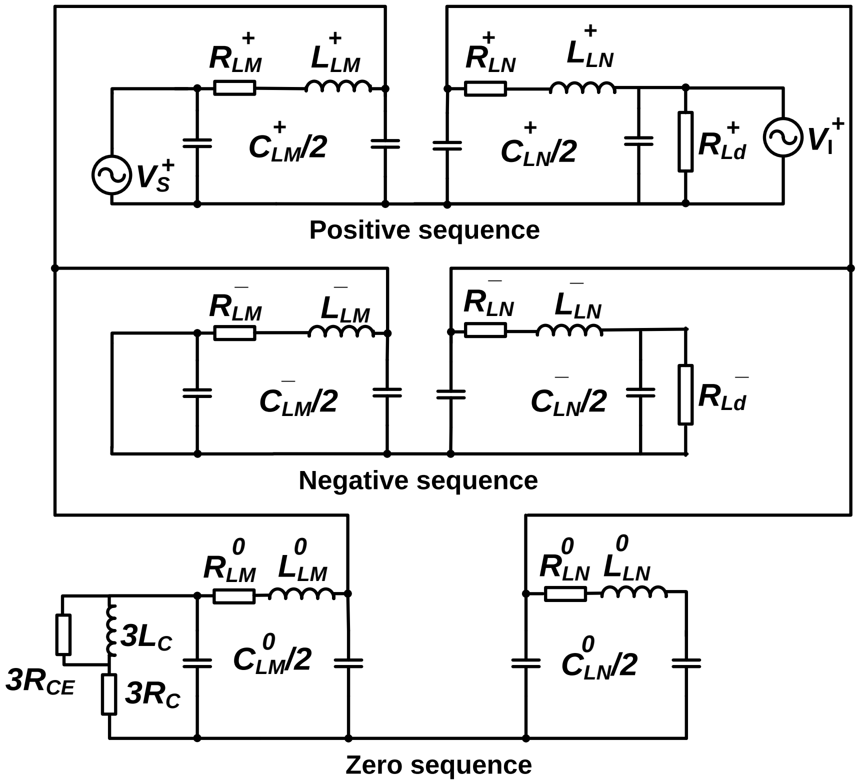


Figure 4.15 Sequence network for the simple system with an open circuit in one conductor and with isolated three phase generation on the load side.

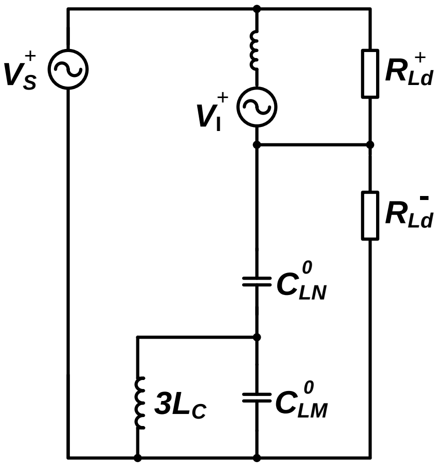


Figure 4.16 Sequence network for the simple system with an open circuit in one conductor, with line inductances and all losses ignored and with isolated three phase generation on the load side.

If the distributed generation is in phase with the main source it will cause a reduction in the neutral voltage with no change in phase angle. Because it is likely to be slightly out of phase, distributed generation will cause a reduction in the magnitude of the neutral voltage together with a small change in phase angle. Networks with isolated three phase generation would need detailed analysis.

The above conclusions for isolated generation have been proven using EMTP simulations with the system represented as shown in Figure 4.17. The arc suppression coil is represented by an ideal inductor of 15.8935 Henries, a resistor of 24,9650 ohms to represent the energising equivalent resistance and a resistor of 99.8619 ohms to represent the equivalent coil resistance. The three phase infinite source is represented by three ideal generators with the output phase angles displaced by 120^0 from each other. The 50 km 11 kV overhead line with an open circuited conductor at the mid-point is represented by two 25 km lines with two phases connected and the third connected through an open switch. The isolated generation is represented by three delta connected ideal generators in series with suitable impedances and with output phase angles to match the output of the three phase source. The delta connected load is represented by three resistors with values chosen to equate to a total load of 100 kW.

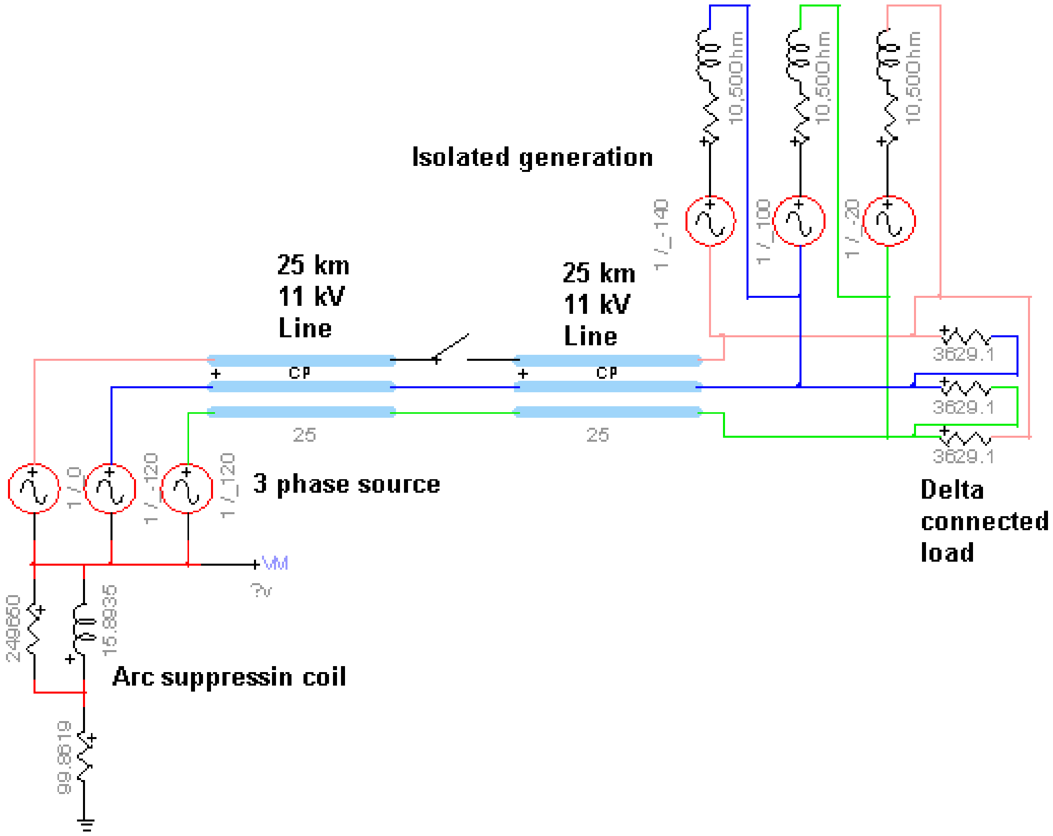


Figure 4.17 EMTP representation of an open circuit in one phase line and isolated generation.

4.5.3 Open circuit with a line to earth fault

To simulate a simultaneous open circuit and line to earth fault at the same location, such as could occur when an overhead conductor breaks and one end falls to the earth, the symmetrical component network, with magnetic coupling, as shown in Figure 4.18 can be used, where R_{FM} and R_{FN} represent the resistance of the line to earth faults on either side of the open circuit. This network is based on the work done by Mortlock on representing simultaneous faults using magnetic coupling[64].

The mathematical calculation of neutral voltage for this network involved solving eighteen simultaneous equations, with eighteen unknown quantities, using a matrix analysis, as set out in Appendix A1.

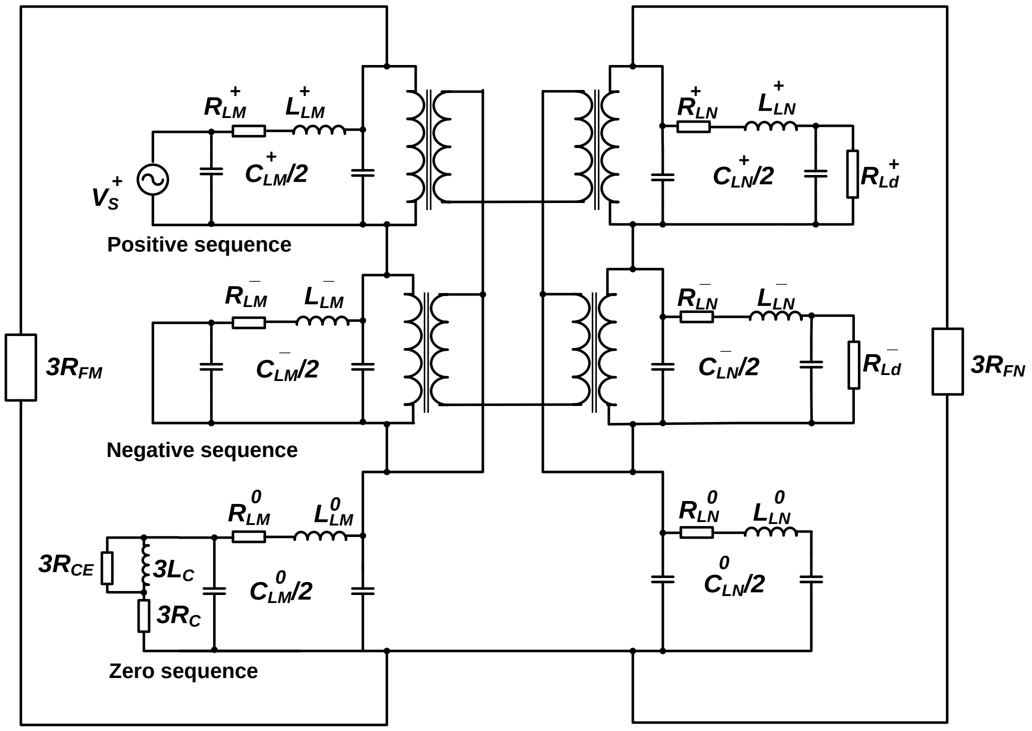
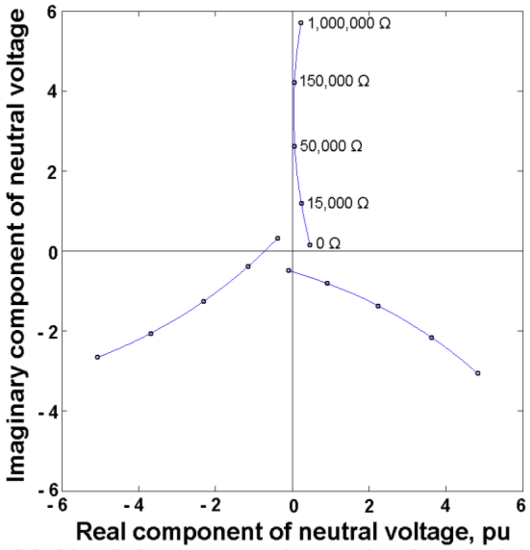


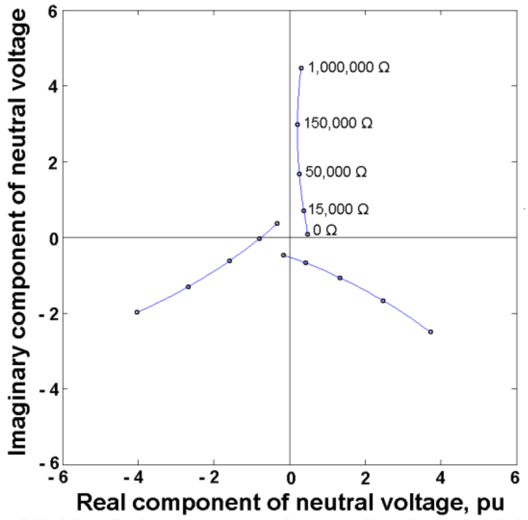
Figure 4.18 Sequence network for the simple system with an open circuit and simultaneous single line to earth faults at the same location and in the same conductor.

This system was analysed for open circuits at three locations in turn for a range of fault resistances, continuously varying from zero to1 MΩ, on either side of the open circuit, and on each phase line in turn. The resulting neutral voltages were plotted as shown in Figures 4.19 and 4.20.

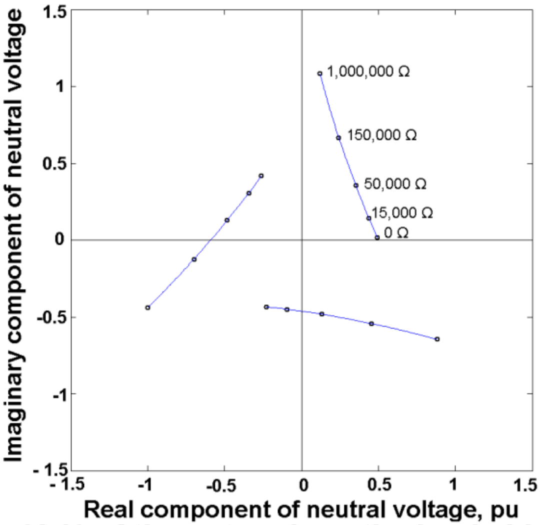
For each fault condition the neutral voltage and phase angle for several fault impedances were checked with EMPT software using both the simple model of Figure 4.1 and the urban zone substation model of Figure 4.6.



90 % of the network on the load side

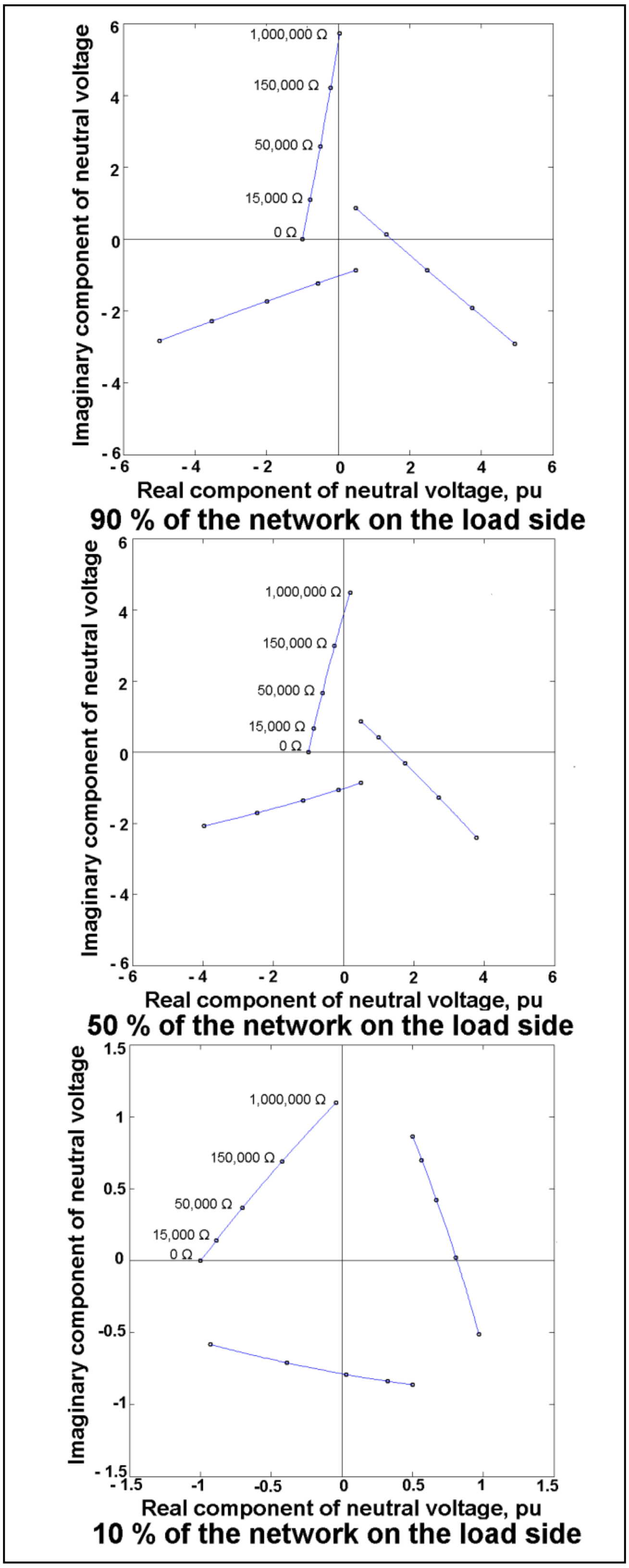


50 % of the network on the load side



10 % of the network on the load side

Figure 4.19 Neutral voltage for an open circuit at three locations, and a line to earth fault at the same location on the load side varying from zero to 1 MΩ, and with faults on each phase line in turn. The reference phase angle is A to N.



90 % of the network on the load side

50 % of the network on the load side

10 % of the network on the load side

Figure 4.20 Neutral voltage for an open circuit at three locations, and a line to earth fault at the same location on the source side varying from zero to 1 MΩ, and with faults on each phase line in turn. The reference phase angle is A to N.

4.6 Appropriate actions to take on detecting an abnormal neutral voltage.

When an abnormal neutral voltage is detected there are several possible protective actions:

- Bypass the arc suppression coil as shown in Figure 4.21.
- Isolate the affected feeder
- Isolate the whole system
- Initiate a line patrol

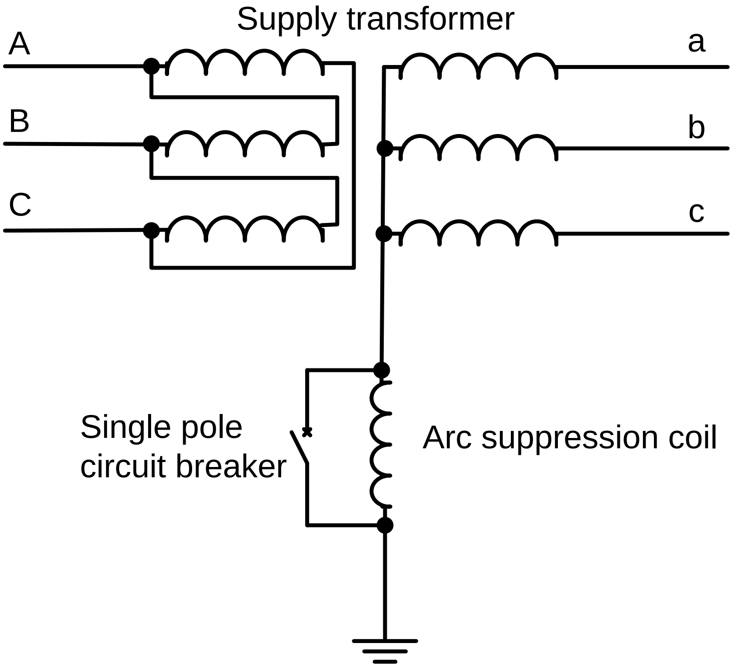


Figure 4.21 Bypassing of arc suppression coil.

In the event of a low impedance earth fault which persists, there is a possibility that the fault could be of a type which can be cleared by bypassing the arc suppression coil so as to apply normal fault current and allowing conventional protection to clear the fault. These fault types include such things as a snake or vermin across an insulator. In power systems fitted with line circuit breakers, reclosers, or sectionalisers, it may also be necessary to apply normal fault current to cause them to operate. However, there is also a possibility that the fault is through a path which involves a human where there are no serious consequences because of the minimal fault current.

For example consider the following hypothetical scenario:

> A vehicle has collided with a pole and as a result a conductor, while not being broken, has become free from its insulator. There is now a conductive path to the vehicle. The situation is such that, while the bypass switch is open and the fault current is almost zero the voltage being applied to the vehicle is minimal. When the bypass switch is closed high voltage is applied to the vehicle.

In this scenario, closing the bypass switch could cause the death or serious injury to an occupant or to another person trying to help.

The dilemma, for the network operator, is to set a policy for the particular geographic area. The data to be considered in setting a policy may include such factors as history of faults, proximity to populated areas, and so on.

A high impedance earth fault which persists could be due to a tree making contact with the line, an insulating component beginning to fail, or it could be due to a more serious event. In this case, the network operator may decide that it is appropriate to leave the line energised and patrol the line using visual, radio interference, thermal imaging, corona discharge, or other techniques.

In the event of an open circuit combined with an earth fault in an overhead system, it may be concluded that a conductor has broken and fallen. An open circuited bridge with an earth fault would seem unlikely. In the event of an open circuit without an earth fault, it could be a broken bridge, a broken conductor with the ends clear of the earth, or the fallen end insulated from the earth by vehicle tyres or other means. This is a situation which could result in death or serious injury. On this basis, it may be decided that any open circuit should be treated as a dangerous situation and the relevant line disconnected from supply immediately.

In the event of a disturbance in capacitive balance without an open circuit, the probable causes would appear to be limited to less likely events such as a fault in star connected capacitor bank. In the absence of star connected capacitor banks on the system, it may be decided that if there is a disturbance in the capacitive balance there may be a dangerous situation and the relevant line should be disconnected from the supply immediately.

If there are one or more star connected capacitor banks in the system, the values of the neutral voltage magnitude and phase angle to be expected in the event that one of the capacitor bank fuses operates can be pre-calculated and programmed into the protection computer. In this case, the appropriate action would be to send an alarm.

In cases where it is decided to disconnect the line from supply, it may be possible to determine the location of the fault based on one of the methods recently developed [21-27] so that only the affected line is isolated. It is worth noting that in the unlikely event of a turn to earth fault within the secondary winding of the star connected supply transformer the neutral voltage will appear the same as for a high impedance line to earth fault. Although this is not a dangerous situation, it is one that should be rectified as quickly as possible. For an internal fault, where there is arcing or high temperatures in one spot, the buchholz relay should initiate a trip. The methods of locating a permanent fault previously mentioned may be useful in eliminating a feeder fault as the cause.

4.7 Evaluation of fault and appropriate actions

By analysing the magnitude and phase angle of the neutral voltage when a fault occurs, it is possible to make some determinations about the type of fault. From an examination of the neutral voltages for various types given in Figures 4.5, 4.8, 4.12, 4.19 and 4.20, it can be seen that the possible faults for each voltage configuration are as shown in Figure 4.22.

In Figure 4.22, it is important to note that the types of faults shown are possible faults. Figure 4.22 can best be understood by following the logic forward and backwards from each possible fault type. While in many cases the fault type can be determined precisely, there are some cases where it can only be narrowed down to two alternatives. For example, it is not possible to distinguish between a low impedance line to earth fault without an open circuit, and a low impedance line to earth fault on the source side of an open circuit. Similarly, a change in line to earth capacitance on one phase cannot always be distinguished from an open circuit with a line to earth fault. Provided the consequent actions to be taken are the same for the indistinguishable types of faults, then this is not a serious impediment. On the other hand, one can categorically state that if the neutral voltage is greater than 1 pu there is an open circuit.

If it is decided to bypass the arc suppression coil in the event of a low impedance fault, the criteria for determining the critical value for a ‘low’ impedance fault would take into account the sensitivity of the conventional earth fault protection. There is no point in bypassing the arc suppression coil for faults that cannot be detected by the conventional protection. Therefore, the criteria for determining the critical value for “close to 1 pu”, may be based on the sensitivity of the conventional earth fault protection.

In this analysis, for phase angles, “close to”, means within a few degrees. For example, in the realistic model analysed here, the appropriate value would be within 0^0 to -2^0 for phase to earth faults of up to an impedance of 100,000 **Ω**, and within 0^0 to -4.5^0 for an open circuit. In all cases the values would need to be set when the actual system parameters are known.

Simultaneous open circuit and line to earth faults are considered to be affecting the same phase line. The incidence of an open circuit in one phase line and a earth fault in another phase line as a result of the same event would appear to be rare.

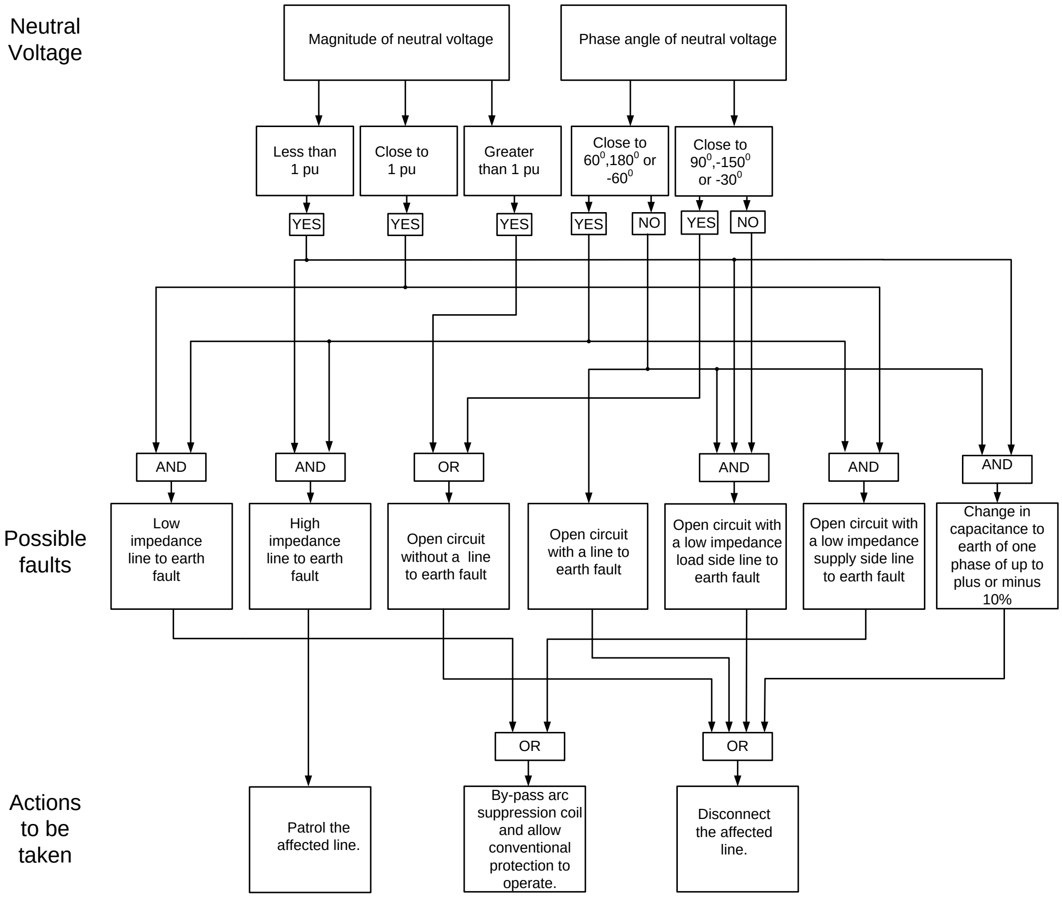


Figure 4.22 Possible fault types and appropriate actions deduced from the neutral voltage.

Automatic whole of substation or system protection equipment, such as that described in [44-46], will be able to take appropriate action immediately on the basis of the neutral voltage using the criteria shown in Figure 4.22.

The actions to follow would depend on the policy adopted by the network company. Those shown in Figure 4.22 are based on one reasonable company policy.

On the basis of the actions set out in Figure 4.22, the logic to take action based on the neutral voltages resolves to that shown in Figure 4.23.

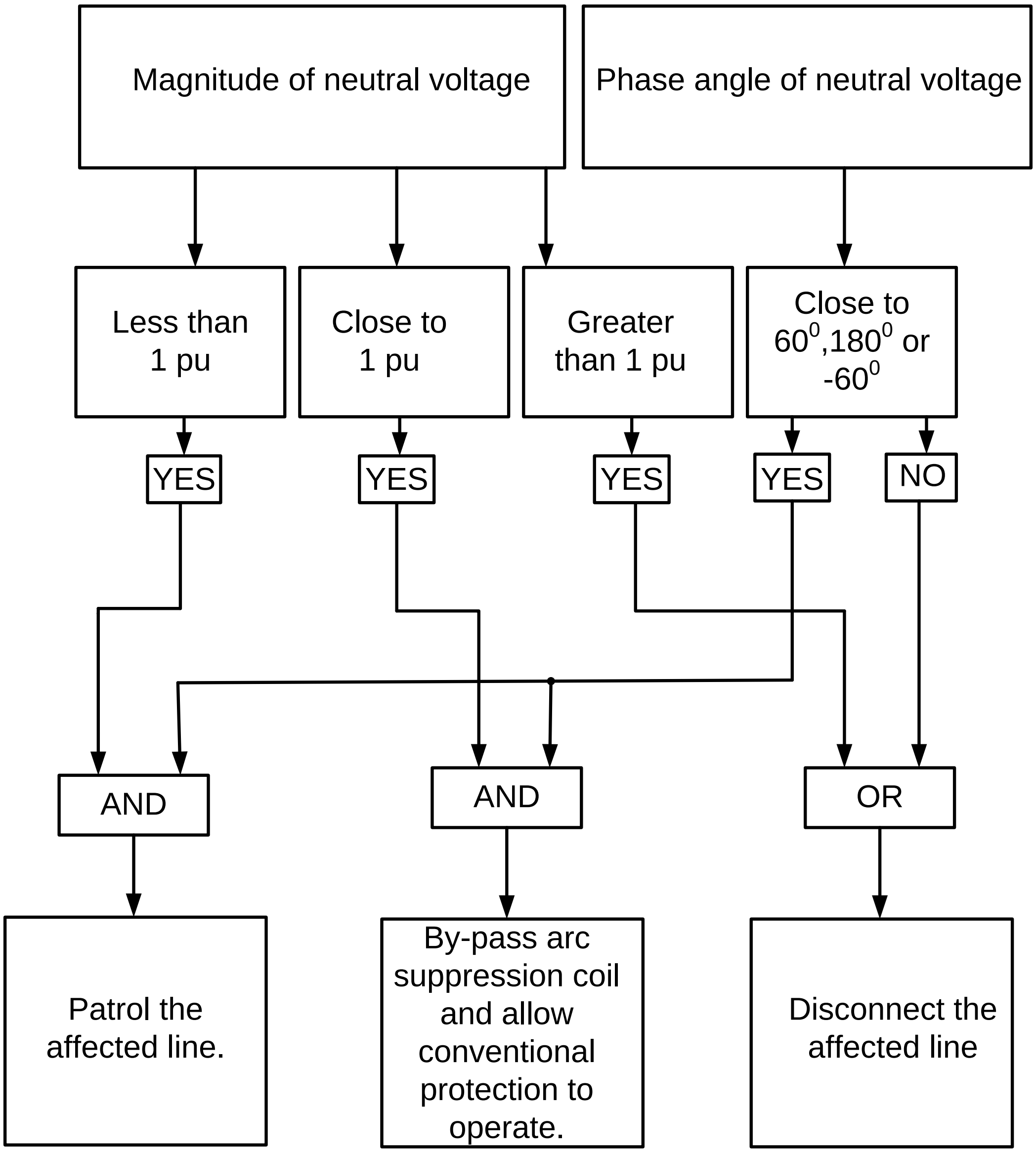


Figure 4.23 Logic for taking action on the basis of the neutral voltage.

It is envisaged that the protection control computer would display and record the possible types of faults as set out in Figure 4.22, but initiate actions based on the logic of Figure 4.23

4.8 Summary

By using a properly tuned arc suppression coil and monitoring the neutral voltage, it is possible to detect high impedance line to earth faults as well as dangerous broken conductor situations which cannot be detected by conventional protection systems.

By monitoring both the phase angle and the magnitude of the neutral voltage, it is possible to automatically diagnose many abnormal conditions on the power system to the extent that decisions can be made on the appropriate action to take.

In at least one country, automatic computerised substation and whole of system protection systems are currently being installed in lieu of individual numeric relays [44-46].

If the substation and/or total power system is fitted with a modern overall computer controlled protection system, the process of diagnosing abnormal system conditions and taking appropriate action can be fully automated.

Chapter 5 IN-LINE VOLTAGE REGULATORS

For arc suppression coil systems to be used in high voltage distribution systems it is necessary for the in-line voltage regulators used to be compatible with their operation. If the regulators provide an alternate electrical path to earth or inhibit the flow of zero sequence currents along the line the arc suppression coil systems will not operate effectively. It is also important that the in-line voltage regulators do not introduce a zero sequence voltage in series with the line because this can cause very high voltages under normal operating conditions. In this chapter these issues are examined in detail and a practical method of providing in-line voltage regulation is proposed. It is also noted that the number of in-line voltage regulators in the system may be economically reduced by installing distributed static VAR compensators using a control scheme such as that described in [65].

5.1 Open-delta regulators

The use of two auto-transformers connected in open-delta to regulate the voltage in three phase high voltage distribution systems has now become common practice, in systems with the neutral of the zone substation transformer effectively earthed, because of cost savings.

A new generalized sequence network representation of a system with open-delta regulators has been developed. This representation provides a tool to calculate the voltages which may occur in proposed power systems. Previous detailed analyses of open-delta voltage regulators did not use symmetrical components [47-49].

An open-delta regulator consists of two auto-transformers connected as shown in Figure 5.1.

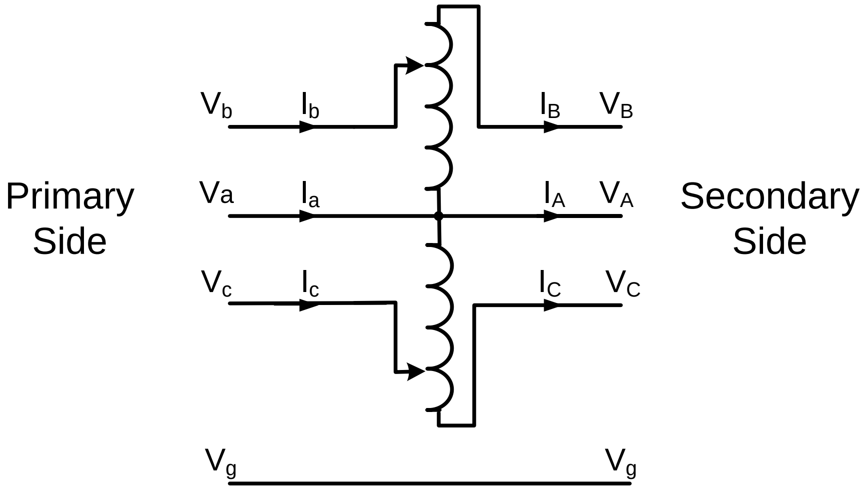


Figure 5.1 Open-delta regulator connections.

Two auto-transformers can conveniently be mounted on a single pole as shown in Figure 5.2

Figure 5.2 Pole mounted open-delta regulator.

The phasor diagram for open-delta regulators can be represented as shown in Figure 5.3.

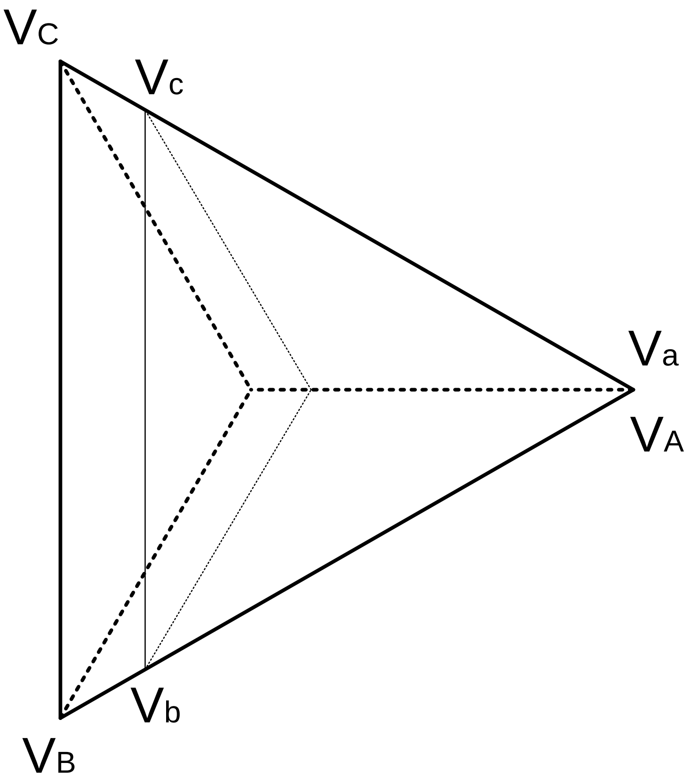


Figure 5.3 Voltage phasor diagram for an open-delta regulator.

Let the transformation ratio be *P* such that:

$$V_{BA} = PV_{ba} \tag{5.1}$$

and:

$$V_{CA} = PV_{ca} \tag{5.2}$$

For ideal open-delta connected auto-transformers the voltage and current relationships can be expressed as follows;

$$V_{Ag} = V_{ag} \tag{5.3}$$

$$V_{Bg} = V_{bg} + (P-1)V_{ba} \tag{5.4}$$

$$V_{Cg} = V_{cg} + (P-1)V_{ca} \tag{5.5}$$

$$I_b = PI_B \tag{5.6}$$

$$I_c = PI_C \tag{5.7}$$

$$I_a = I_A - (P-1)I_B - (P-1)I_C \tag{5.8}$$

5.1.1 Modelling of open-delta regulators using symmetrical components

To analyse the neutral voltages and currents in circuits containing open-delta regulators it is appropriate to use symmetrical components.

Let V_S^+, V_S^- and V_S^0 be the positive, negative and zero sequence secondary voltages respectively.

Let V_P^+, V_P^- and V_P^0 be the positive, negative and zero sequence primary voltages respectively.

Let I_S^+, I_S^- and I_S^0 be the positive, negative and zero sequence secondary currents respectively.

Let I_P^+, I_P^- and I_P^0 be the positive, negative and zero sequence primary currents respectively.

By definition:

$$\begin{pmatrix} V_S^0 \\ V_S^+ \\ V_S^- \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix} . \begin{pmatrix} V_{Ag} \\ V_{Bg} \\ V_{Cg} \end{pmatrix} \tag{5.9}$$

From (5.3), (5.4), (5.5) and (5.9) we get:

$$\begin{pmatrix} V_S^0 \\ V_S^+ \\ V_S^- \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix} . \begin{pmatrix} V_{ag} \\ V_{bg} \\ V_{cg} \end{pmatrix} + \frac{P-1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix} . \begin{pmatrix} 0 \\ V_{ba} \\ V_{ca} \end{pmatrix}$$

$$= \begin{pmatrix} V_P^0 \\ V_P^+ \\ V_P^- \end{pmatrix} + \frac{P-1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix} . \begin{pmatrix} 0 \\ V_{ba} \\ V_{ca} \end{pmatrix} \tag{5.10}$$

$$V_S^0 = V_P^0 + \frac{P-1}{3}\left(V_{ba} + V_{ca}\right)$$

$$= V_P^0 + \frac{P-1}{3}\left(V_{bg} - V_{ag} + V_{cg} - V_{ag}\right) \tag{5.11}$$

However:

$$\begin{pmatrix} V_{ag} \\ V_{bg} \\ V_{cg} \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix} . \begin{pmatrix} V_S^0 \\ V_S^+ \\ V_S^- \end{pmatrix} \tag{5.12}$$

Therefore from (5.11) and (5.12) we have:

$$V_S^0 = V_P^0 + \frac{P-1}{3}\left[\left(a^2 - 1\right)V_S^+ + \left(a-1\right)V_S^-\right] + \frac{P-1}{3}\left[\left(a-1\right)V_S^+ + \left(a^2-1\right)V_S^-\right]$$

$$= V_P^0 - (P-1)\left(V_S^+ + V_S^-\right) \tag{5.13}$$

From (5.10) we get:

$$V_S^+ = V_P^+ + \frac{P-1}{3}\left(aV_{ba} + a^2 V_{ca}\right)$$

$$= V_P^+ + \frac{P-1}{3}\left[a\left(V_{bg} - V_{ag}\right) + a^2\left(V_{cg} - V_{ag}\right)\right]$$

$$= V_P^+ + \frac{P-1}{3}\left[aV_{bg} + a^2 V_{cg} - \left(a^2 + a\right)V_{ag}\right]$$

$$= V_P^+ + \left(P-1\right)V_P^+ = PV_P^+ \tag{5.14}$$

Similarly, from (5.10) we get:

$$V_S^- = V_P^- + \frac{P-1}{3}\left(a^2 V_{ba} + aV_{ca}\right)$$

$$= V_P^- + \frac{P-1}{3}\left[a^2\left(V_{bg} - V_{ag}\right) + a\left(V_{cg} - V_{ag}\right)\right]$$

$$= V_P^- + \frac{P-1}{3}\left[a^2 V_{bg} + aV_{cg} - \left(a^2 + a\right)V_{ag}\right]$$

$$=V_P^- + \left(P-1\right)V_P^- = PV_P^- \tag{5.15}$$

From (5.8) we get:

$$I_a = I_A + (1-P)(I_B + I_C)$$

$$= I_A + I_B + I_C - P(I_B + I_C)$$

$$= I_A + I_B + I_C - P(3I_S^0 - I_A)$$

$$= PI_A + 3I_S^0(1-P)$$

$$= P\left[I_A + 3I_S^0\left(\frac{1-P}{P}\right)\right] \tag{5.16}$$

By definition:

$$\begin{pmatrix} I_P^0 \\ I_P^+ \\ I_P^- \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix}.\begin{pmatrix} I_a \\ I_b \\ I_c \end{pmatrix} \tag{5.17}$$

From (5.6), (5.7), (5.16) and (5.17) we get:

$$\begin{pmatrix} I_P^0 \\ I_P^+ \\ I_P^- \end{pmatrix} = \frac{P}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix}.\begin{pmatrix} I_A \\ I_B \\ I_C \end{pmatrix} + \frac{P}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix}.\begin{pmatrix} 3I_S^0\left(\frac{1-P}{P}\right) \\ 0 \\ 0 \end{pmatrix} \tag{5.18}$$

$$I_P^0 = \frac{P}{3}\left(I_A + I_B + I_C\right) + PI_S^0\left(\frac{1-P}{P}\right)$$

$$= \frac{P}{3}\left(I_A + I_B + I_C\right) + \left(I_A + I_B + I_C\right)\left(\frac{1-P}{3}\right)$$

$$= \frac{1}{3}\left(I_A + I_B + I_C\right) = I_S^0 \tag{5.19}$$

From (5.18) we get:

$$I_P^+ = \frac{P}{3}\left(I_A + aI_B + a^2 I_C\right) + PI_S^0\left(\frac{1-P}{P}\right)$$

$$= PI_S^+ + I_S^0(1-P) \tag{5.20}$$

From (5.18) we get:

$$I_P^- = \frac{P}{3}\left(I_A + a^2 I_B + aI_C\right) + PI_S^0\left(\frac{1-P}{P}\right)$$

$$= PI_S^- + I_S^0(1-P) \tag{5.21}$$

All of the sequence equations (5.13), (5.14), (5.15), (5.19), (5.20) and (5.21) are satisfied by the symmetrical component model with magnetic coupling as shown in Figure 5.4. It is interesting to compare this symmetrical representation with the phasor diagram in Figure 5.3. As expected, the positive sequence voltage is increased by the auto-transformer ratio. A negative sequence voltage would be similarly increased. It can be seen from both Figure 5.3 and Figure 5.4 that the zero sequence voltage induced is relative to both the magnitude of the positive sequence voltage and the auto-transformer ratio. As would be expected from the fact that there is no neutral connection, the primary and secondary zero sequence currents are equal.

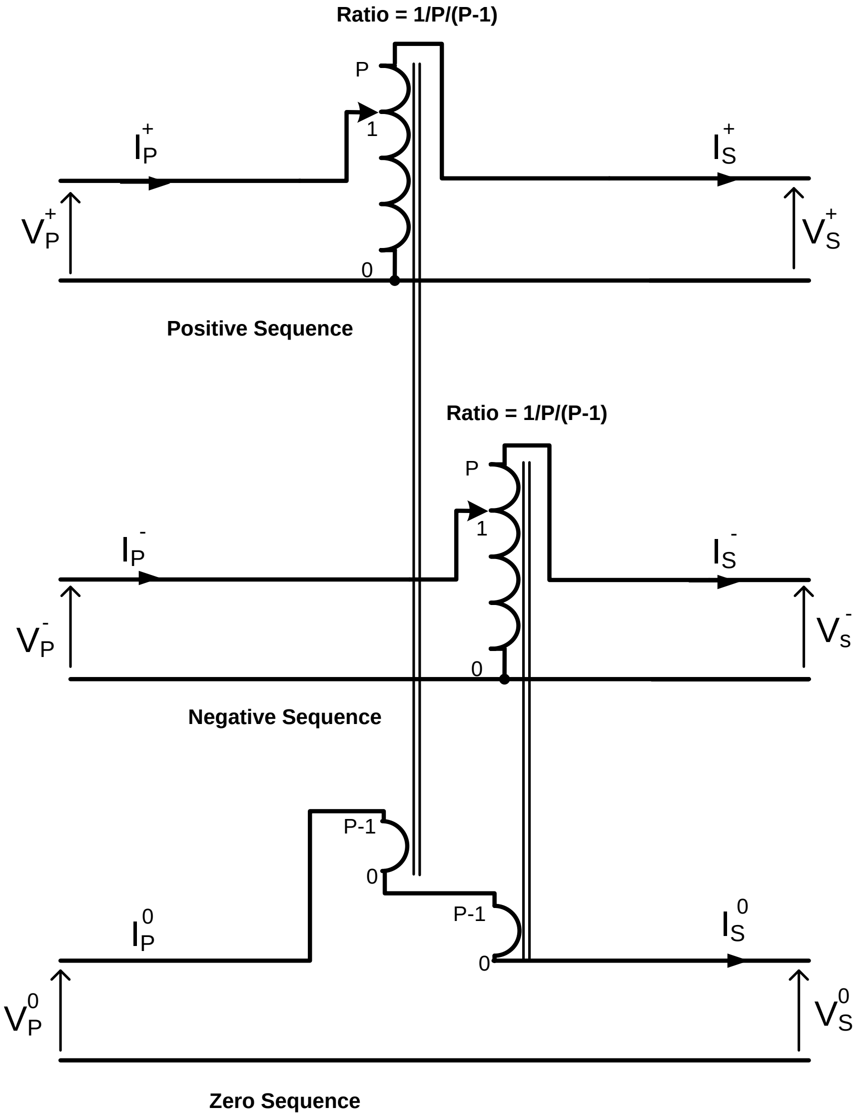


Figure 5.4 Symmetrical component representation of an open-delta regulator.

5.1.2 Analysis of a simple system with open delta regulators

Consider the simple 11 kV overhead system shown in Figure 5.5. A single length of line is supplied by the star winding of a transformer. The transformer neutral is earthed through an inductor tuned to the total system line to earth capacitance. An open-delta regulator with a 10% boost is installed mid way along the line. The line is simplified to show the distributed line to earth capacitances as combined into lumped capacitances at the ends of each line segment.

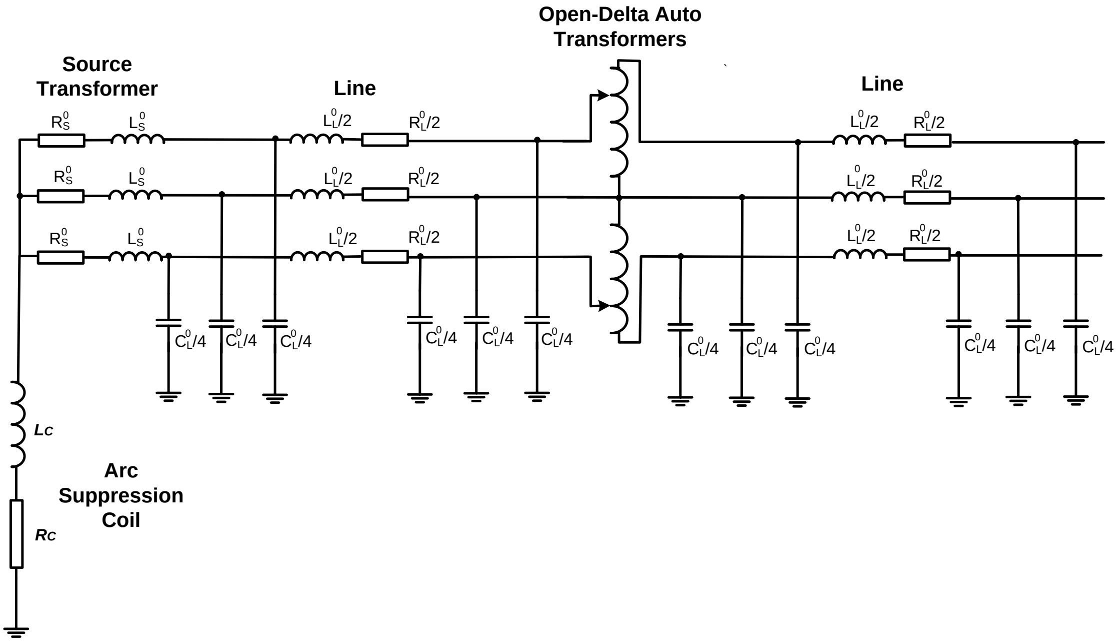


Figure 5.5 Simple 11 kV System showing zero sequence and earthing components.

The arc suppression coil is tuned to the system capacitance to earth such that:

$$3\omega L_C = \frac{1}{\omega C_L^0} \tag{5.22}$$

where L_C represents the total of the arc suppression coil and the supply transformer zero sequence inductances.

The zero sequence symmetrical components can be used to analyse the over-voltages as shown in Figure 5.6. The effect of the open-delta regulator is to increase the positive sequence voltage and also to introduce a zero sequence voltage change.

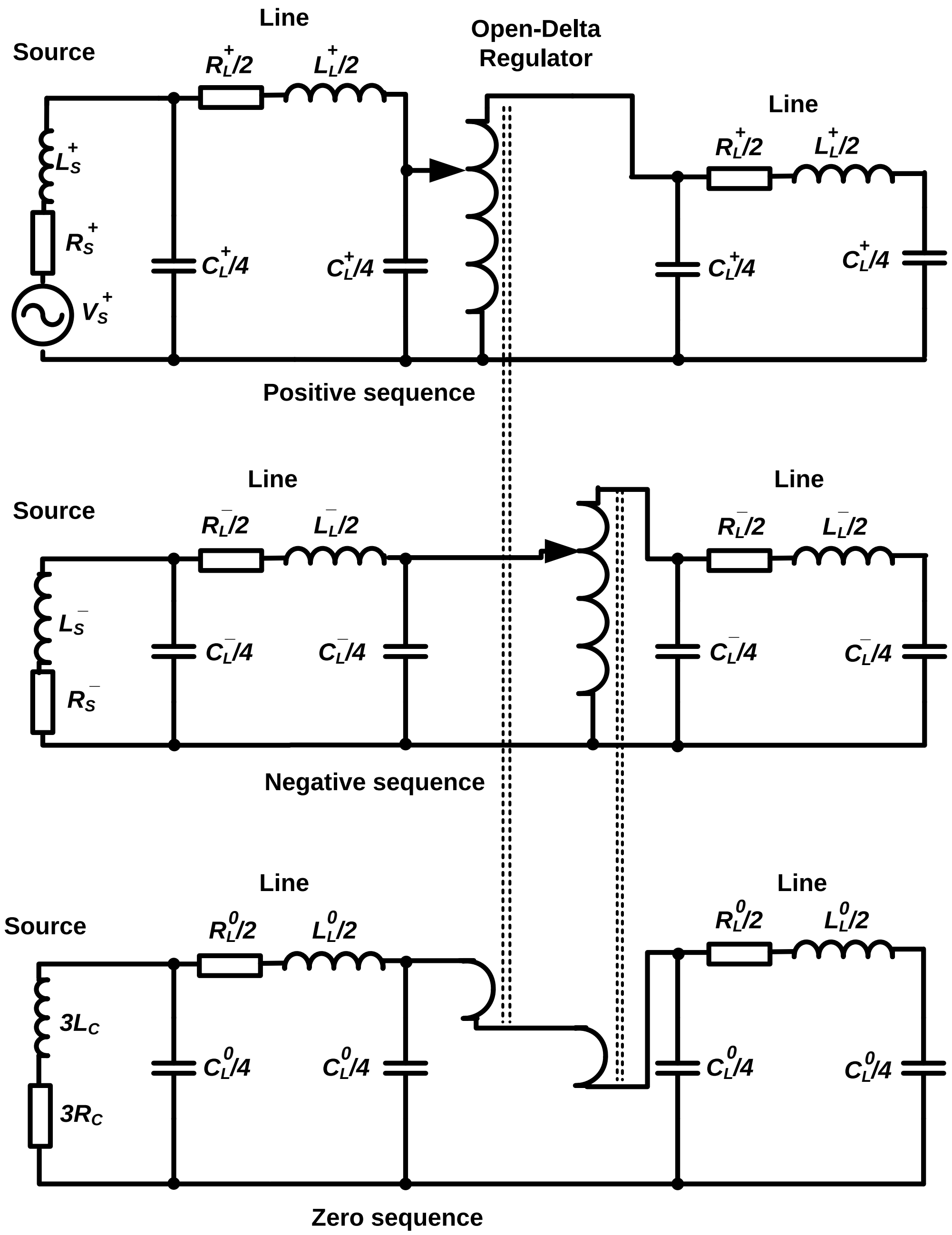


Figure 5.6 Symmetrical component representation of a simple system with an open-delta voltage regulator.

To evaluate the over-voltages the transformers were eliminated by referring all impedances and the supply voltage to the zero sequence network side of the transformers as shown in Figure 5.7. Also, the source impedances have been ignored in this exercise because they are insignificant when referred to the zero sequence network.

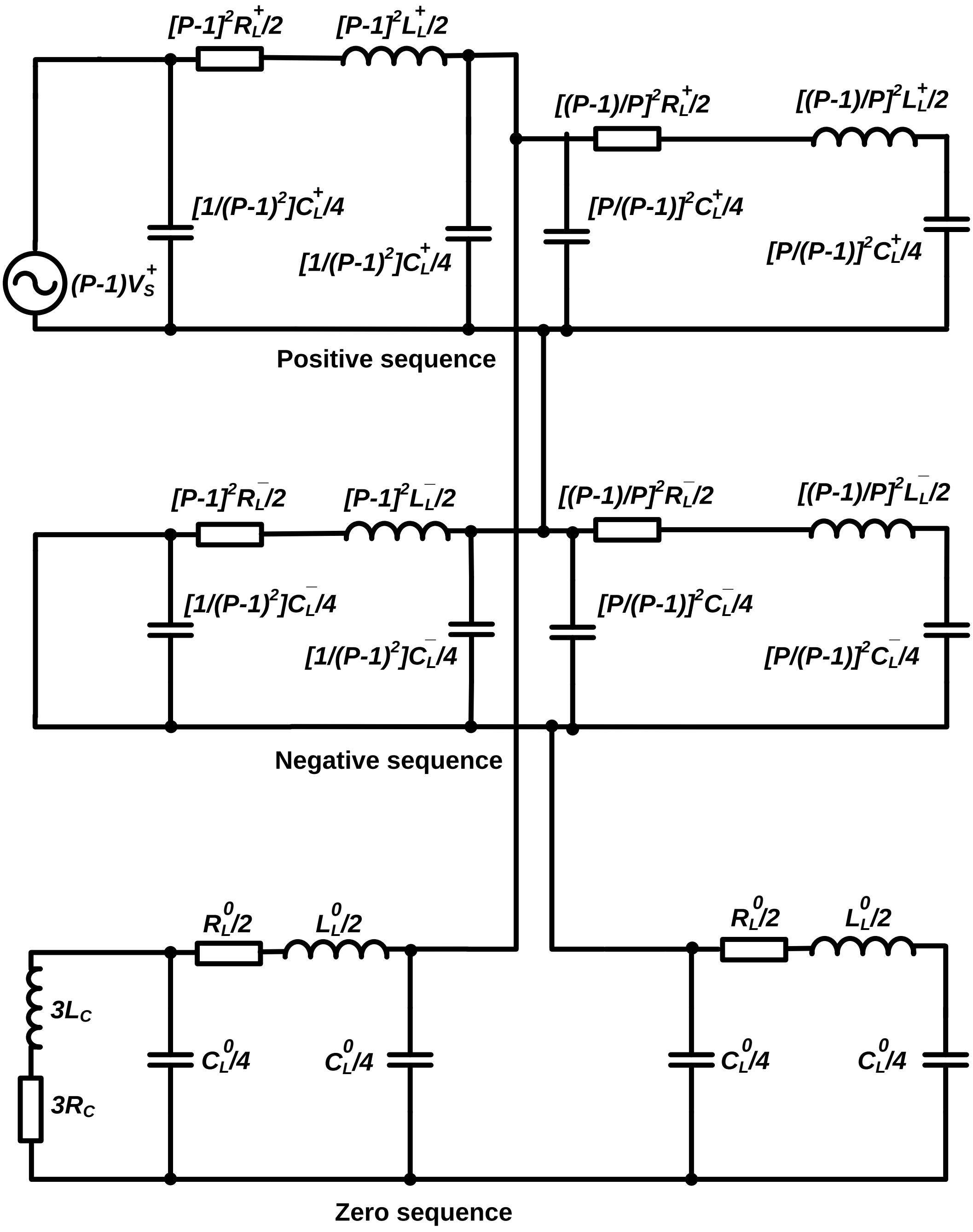


Figure 5.7 Sequence network representation of the simple system with an open-delta regulator referred to the zero sequence side.

The following realistic parameter values were assumed;

Voltage regulator boost ratio ***P*** = 1.1

Line positive, negative and zero sequence resistance values;

R_L^+, R_L^- and $R_L^0 = 20\ \Omega$

Line positive and negative reactance values, L_L^+ and $L_L^- = 70$ mH

Line positive and negative capacitance values, C_L^+ and $C_L^- = 0.25$ µF

Line zero sequence inductance, $L_L^0 = 200$ mH

Line zero sequence capacitance, $C_L^0 = 0.17$ µF

Positive sequence source voltage, $V_S^+ = 6{,}350$ V

Arc suppression coil resistance, $R_C = 20\ \Omega$

From (5.22) the arc suppression coil inductance, $L_C = 19.8669$ H

Using these values, an analysis of the sequence network, as shown in Figure 5.7, gives a zero sequence voltage and thus a neutral voltage at the source transformer of 86 kV. The three phase system with distributed line capacitances was then analysed using the EMTP software as shown in Figure 5.8.and the corresponding voltage obtained was within 1.4% of this value, thus confirming the sequence analysis and calculation.

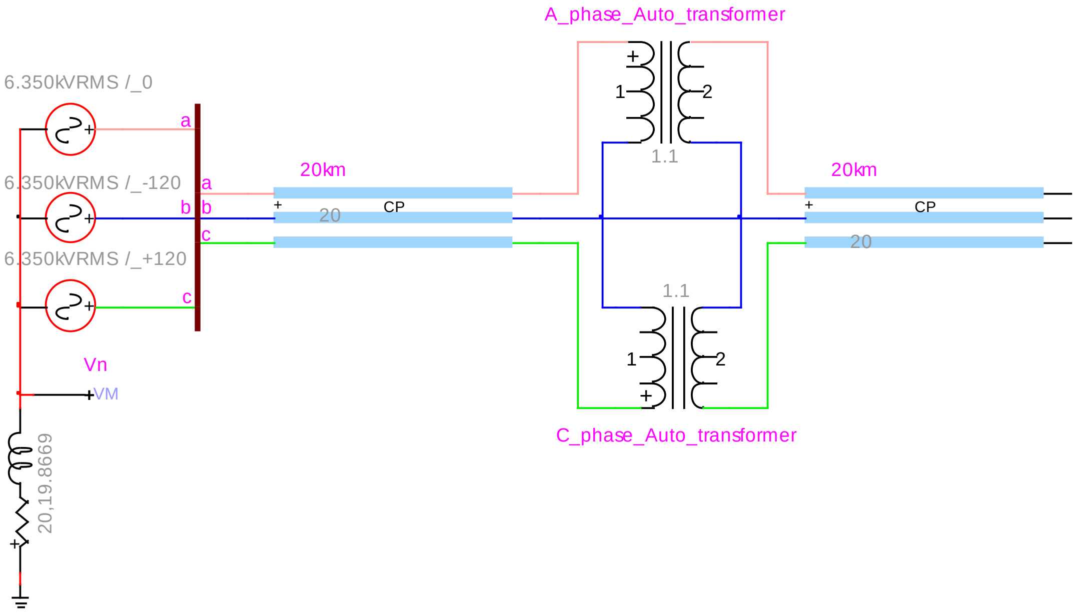


Figure 5.8 EMTP Representation of the simple system with an open-delta voltage regulator.

A clearer understanding of the issue may be gained by considering a theoretical simple system which has negligible source and line inductances and no losses. The sequence network then resolves to that shown in Figure 5.9.

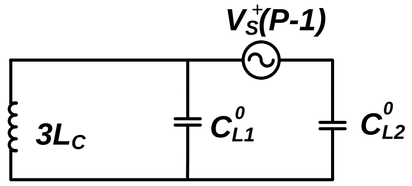


Figure 5.9 Sequence Network for the simple system with line inductances and all losses ignored.

Let Y_L be the zero sequence admittance of the arc suppression coil.

Let Y_{C1} be the zero sequence admittance of the capacitance to earth of the line on the source side of the open-delta regulator.

Let Y_{C2} be the zero sequence admittance of the capacitance to earth of the line on the load side of the open-delta regulator.

If the arc suppression coil is correctly tuned to the line to earth capacitances then the sum of the admittances will be zero. Therefore:

$$Y_L + Y_{C1} + Y_{C2} = 0 \qquad (5.23)$$

$$Y_L + Y_{C1} = -Y_{C2} \qquad (5.24)$$

Let I^0 be the total zero sequence current. Then:

$$I^0 = \frac{V_S^+(P-1)}{\dfrac{1}{Y_L + Y_{C1}} + \dfrac{1}{Y_{C2}}} \qquad (5.25)$$

From (5.24) and (5.25) we get:

$$I^0 = \frac{V_S^+(P-1)}{\dfrac{1}{-Y_{C2}} + \dfrac{1}{Y_{C2}}} = \infty \qquad (5.26)$$

The zero sequence current can be very large regardless of the position of the open-delta regulator in the high voltage line, provided there is significant line to earth capacitance on the load side.

If the system is slightly detuned and/or a saturable magnetic core is used for the earthing inductor the voltages will be much lower but can still reach dangerous values. However detuning the inductor reduces the sensitivity to high impedance earth faults.

Using EMTP software as shown in Figure 5.10, an earthing inductor was simulated having a saturable magnetic core and an air gap, a magnetizing resistance of 50 pu and a winding resistance 0.02 pu. The magnetising characteristic for the saturable core is shown in Figure 5.11. Although not apparent in the scale used, there is a small magnetising current up to the point of saturation of the core at about 39 Webers.

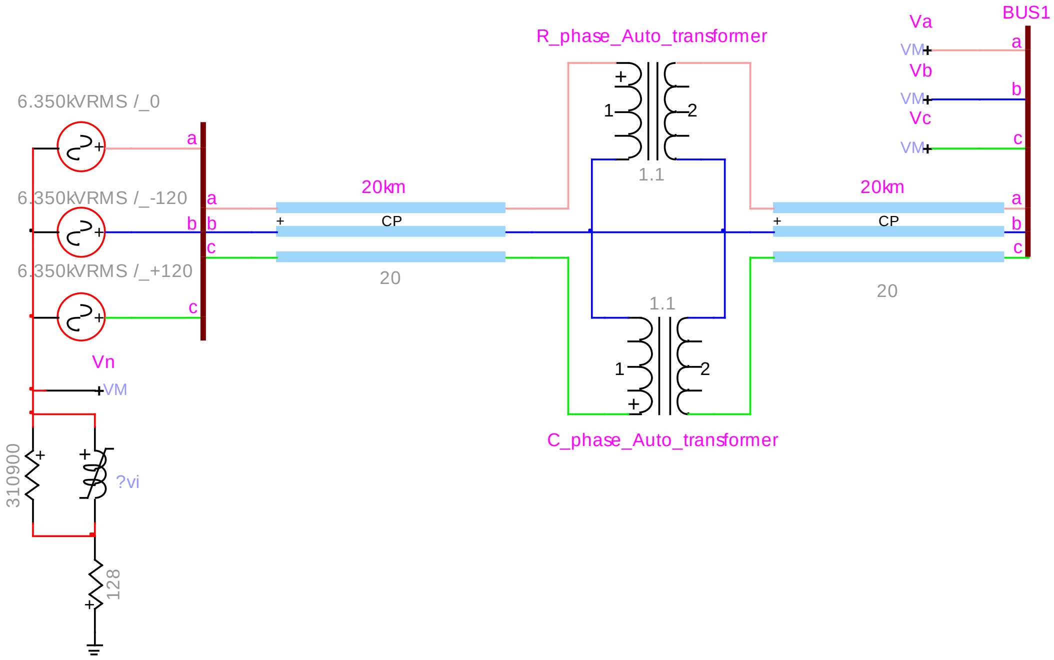


Figure 5.10 EMTP Representation of the simple system with an open-delta voltage regulator and a saturable magnetic cored suppression coil.

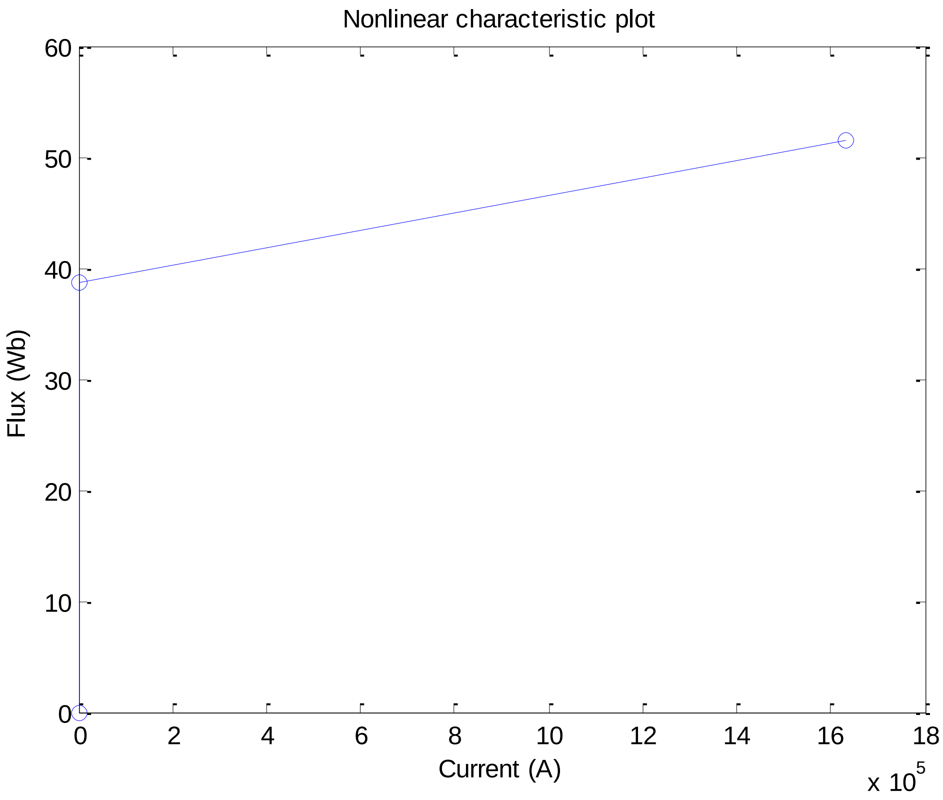


Figure 5.11 Magnetizing curve of the earthing inductor.

For the simple system the resulting neutral voltage as calculated by the EMTP software was 7.66 kV. The phase voltages were as shown in Figure 5.12. The maximum phase to earth voltage was 14.2 kV. This is in excess of the rated insulation level of a typical 11 kV system.

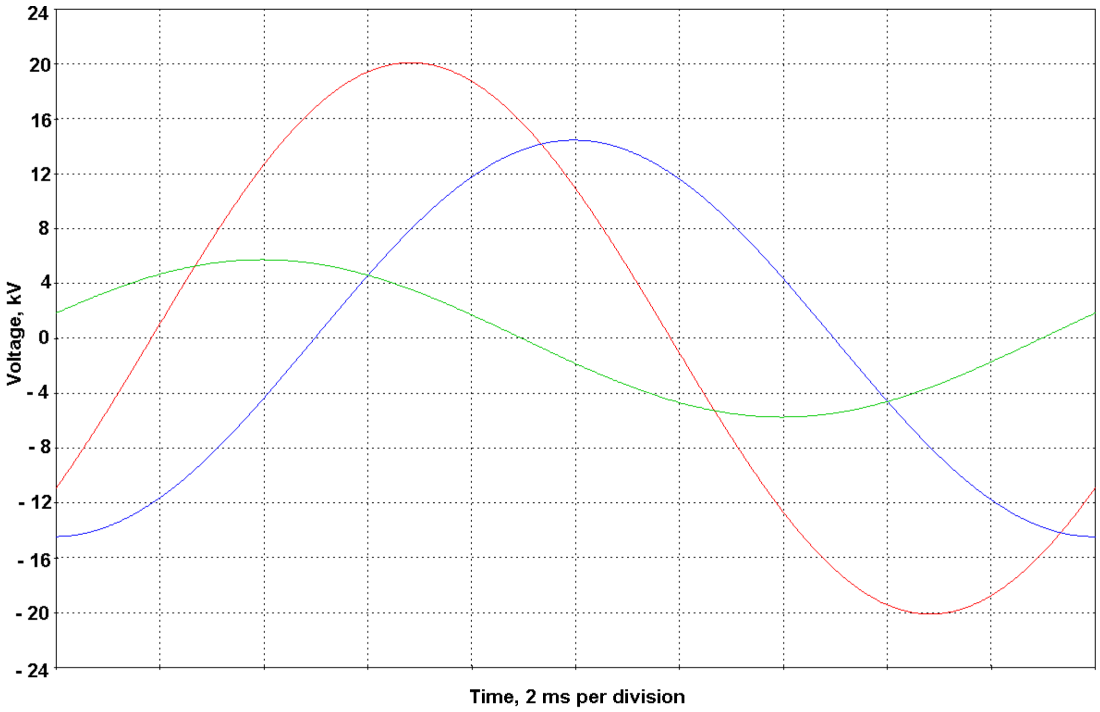


Figure 5.12 Phase voltages for the simple system with a practical, saturable earthing inductor and a voltage regulator ratio of 1.1.

An arc suppression coil and open-delta voltage regulators should not be installed in the same power system because of the dangerous voltages that can occur under normal operating conditions.

5.2 Three star connected auto-transformers

Let us consider the use of three star connected auto-transformers. Whereas two auto-transformers are commonly mounted on a single pole as shown in Figure 5.13, three auto-transformers can also be mounted on a single pole as shown in Figure 5.14.

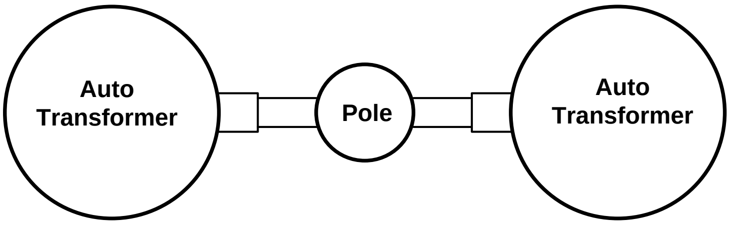


Figure 5.13 Two auto-transformers mounted on a single pole

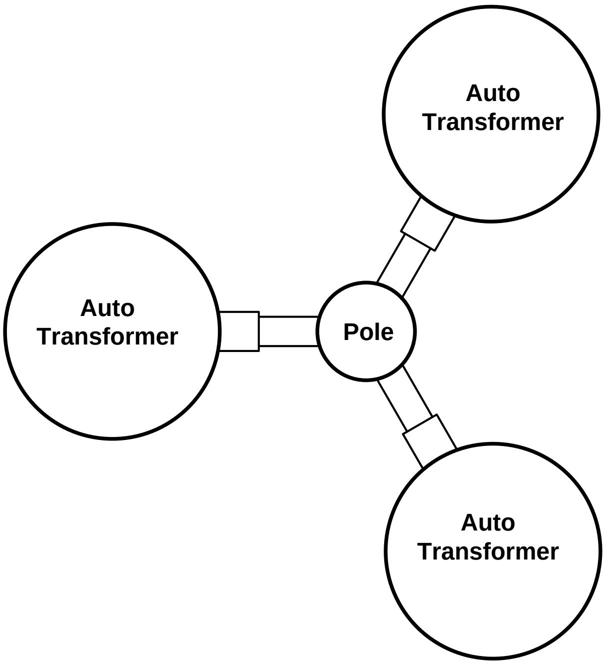


Figure 5.14 Three auto-transformers mounted on a single pole.

There are various methods of connecting the three auto-transformers.

5.2.1 Three star connected single phase auto-transformers with the star point earthed

Let us consider the use of three single phase auto-transformers connected in star with the star point earthed as shown in Figure 5.15.

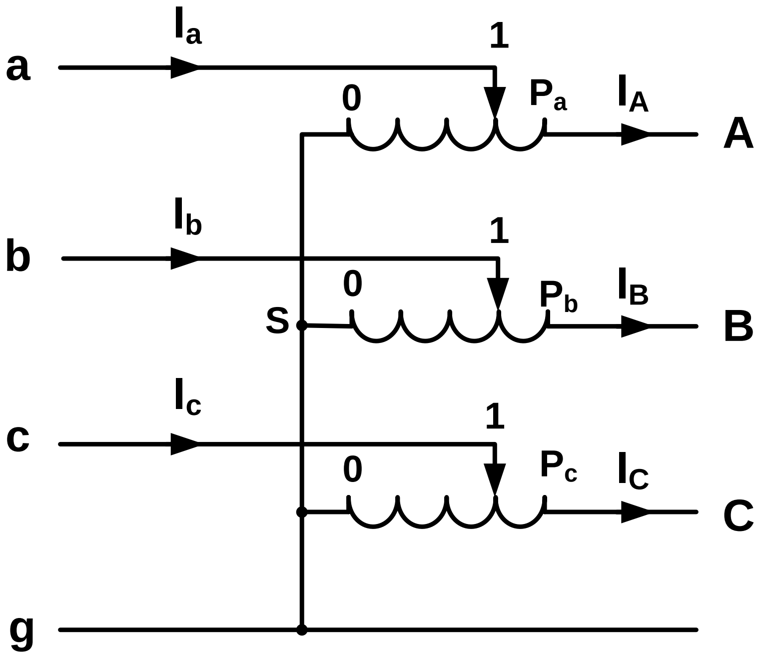


Figure 5.15 Three star connected auto-transformer with the star point earthed voltage regulator connections.

The zero sequence representation of this arrangement, with all three of the auto-transformer ratios equal to P, is as shown in Figure 5.16.

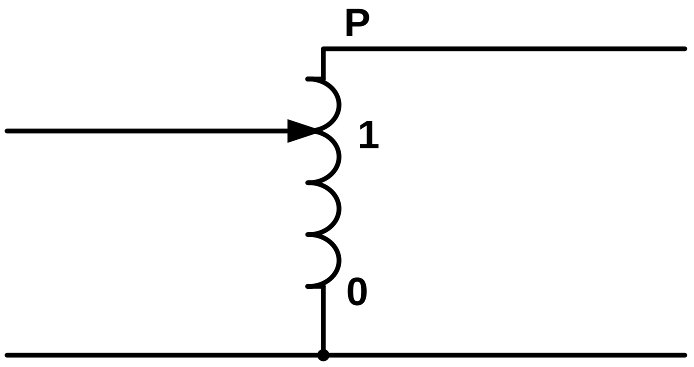


Figure 5.16 Zero sequence representation of a three star connected auto-transformers with the star point earthed

The use a three star connected auto-transformer with the star point earthed would mean that the admittance value of the line to earth capacitances as reflected on the other side of the auto-transformers would change by the auto-transformer ratio squared. To keep the system accurately tuned it would be necessary to adjust the arc suppression coil system inductance as the auto- transformer ratios changed. The auto-transformers would also need to be designed so that the energising current is not excessive when the line to line to voltage is applied during a line to earth fault.

5.2.2 Three star connected single phase auto-transformers with the star point unearthed

Let us consider the use of three single phase auto-transformers connected in star with the star point unearthed as shown in Figure 5.17.

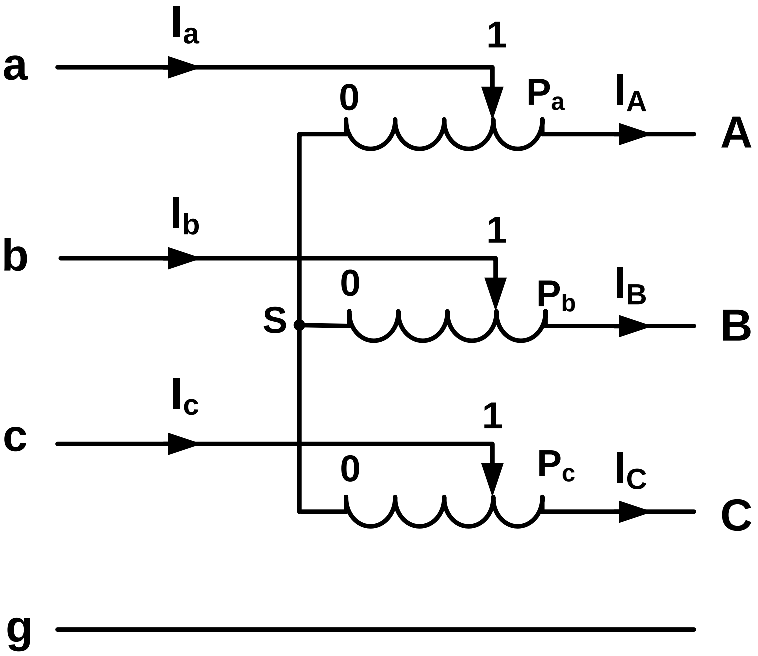


Figure 5.17 Three star connected auto-transformers with the star point unearthed voltage regulator connections.

Let the transformation ratios be P_a, P_b and P_c such that:

$$V_{AS} = P_a V_{aS} \tag{5.27}$$

$$V_{BS} = P_b V_{bS} \tag{5.28}$$

$$V_{CS} = P_c V_{cS} \tag{5.29}$$

Let I_a, I_b and I_c be the respective primary line currents.

Let I_A, I_B and I_C be the respective secondary line currents.

For ideal transformers the current relationships can be expressed as follows:

$$I_a = P_a I_A \tag{5.30}$$

$$I_b = P_b I_B \tag{5.31}$$

$$I_c = P_c I_C \tag{5.32}$$

Summing the currents at the star point gives;

$$0 = (P_a - 1)I_A + (P_b - 1)I_B + (P_c - 1)I_C \tag{5.33}$$

Let us consider the case where:

$$P_a = P_b = P_c = P$$

Then from (7) we get:

$$0 = (I_A + I_B + I_C)(P - 1) \tag{5.34}$$

But:

$$I_S^0 = \frac{1}{3}\left(I_A + I_B + I_C\right) \tag{5.35}$$

where I_S^0 is the zero sequence current on the load side of the in-line regulator.

Therefore from (5.34) and (5.35) we have:

$$0 = 3I_S^0(P - 1) \tag{5.36}$$

Therefore the zero sequence representation of three star connected auto-transformers with identical ratios (p), and the star point unearthed is as shown in Figure 5.18.

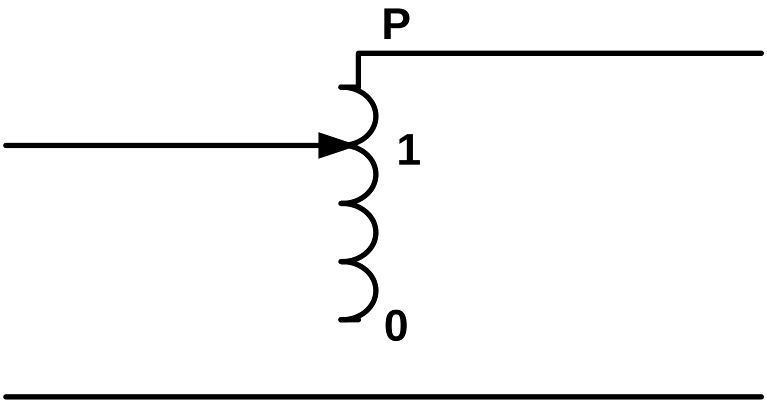


Figure 5.18 Zero sequence representation of a three star connected auto-transformers with the star point unearthed.

When a regulator is used in an arc suppression coil system it is important, for optimum arc extinction, that the configuration does not present any significant impedance to the zero sequence currents flowing along the line. Equation (5.36) and Figure 5.18 show that if the ratios of the three auto-transformers are identical and not equal to unity there can be no zero sequence current through this star connected auto-transformer arrangement. Therefore the star connected auto-transformer configuration as shown in Figure 5.17 should not be used in arc suppression coil power systems.

It is noted that unless a three phase star connected and unearthed auto-transformer also had a delta connected tertiary winding it would similarly hinder the optimum operation of the arc suppression coil system because of the zero sequence impedance. A three phase voltage regulator of the capacity usually needed entails the establishment of a earth type substation. This is considerably more expensive than single phase auto-transformers mounted on a single pole.

5.3 Three delta connected single phase auto-transformers.

An alternative method of using three auto-transformers mounted on a single pole is to connect them in a closed-delta arrangement as shown in Figure 5.19.

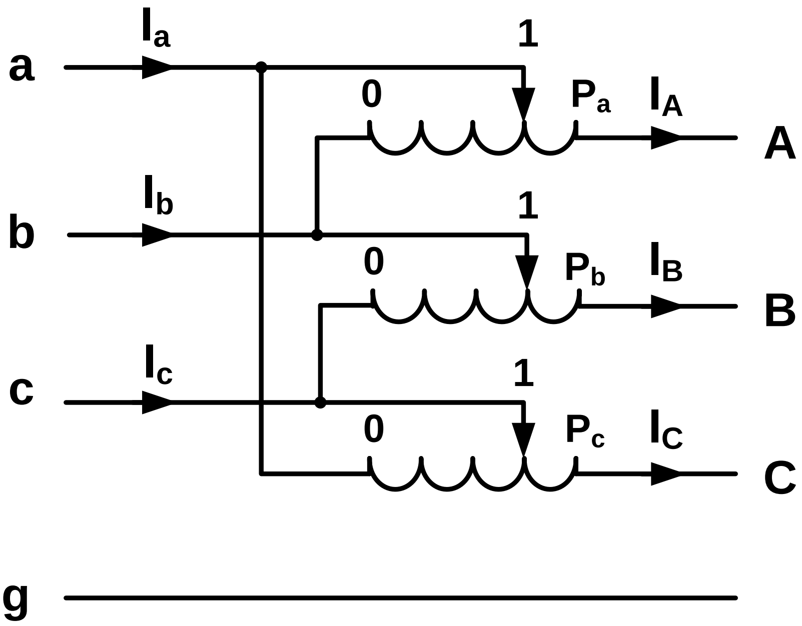


Figure 5.19 Three delta connected auto-transformers voltage regulator connections

5.3.1 Modelling of three delta connected auto-transformers using symmetrical components.

The phasor diagram for normal operation of a three delta connected auto-transformer voltage regulator is as shown in Figure 5.20.

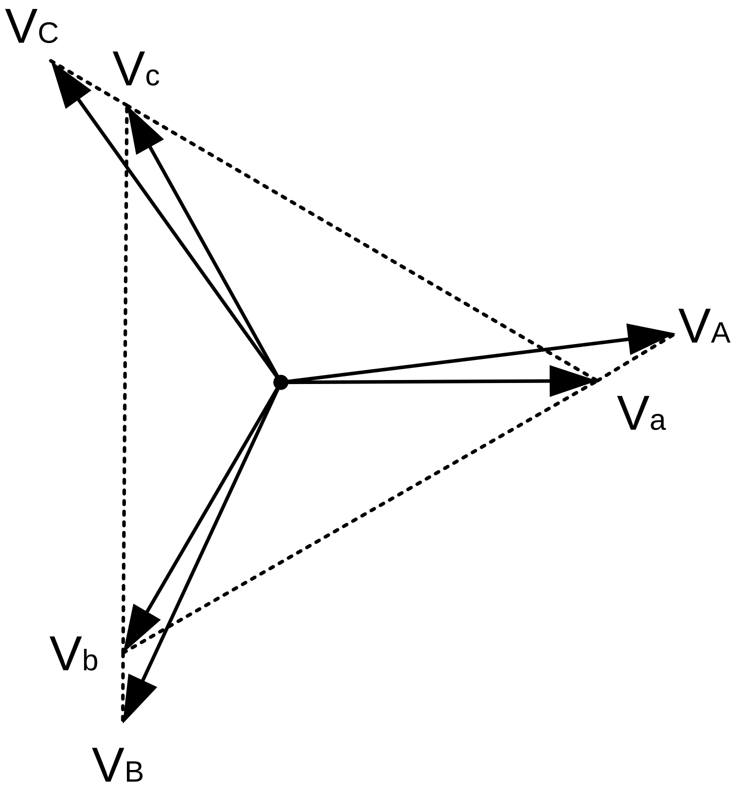


Figure 5.20 Phasor diagram for the normal operation of a three delta connected auto-transformer voltage regulator.

Let the transformation ratios be P_a, P_b and P_c such that:

$$V_{Ab} = P_a V_{ab} \tag{5.37}$$

$$V_{Bc} = P_b V_{bc} \tag{5.38}$$

$$V_{Ca} = P_c V_{ca} \tag{5.39}$$

The for ideal transformers current relationships are then as shown in Figure 5.21

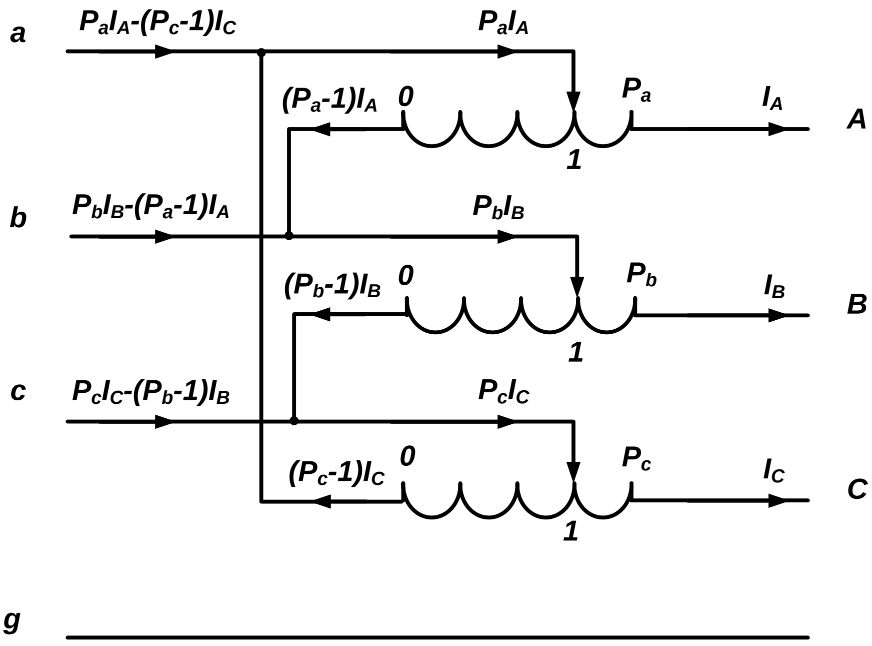


Figure 5.21. Currents in a three delta connected auto-transformer voltage regulator.

Then the current relationships can be expressed as follows:

$$I_a = P_a I_A - (P_c - 1) I_C \tag{5.40}$$

$$I_b = P_b I_B - (P_a - 1) I_A \tag{5.41}$$

$$I_c = P_c I_C - (P_b - 1) I_B \tag{5.42}$$

To analyse the neutral voltages and currents it is appropriate to use symmetrical components.

Let I_P^0 and I_S^0 be the primary and secondary zero sequence currents respectively.

By definition:

$$I_P^0 = \frac{1}{3}\left(I_a + I_b + I_c\right) \tag{5.43}$$

From (5.40), (5.41), (5.42) and (5.43) we get:

$$I_P^0 = \frac{1}{3}\left[P_a I_A - (P_c - 1) I_C + P_b I_B - (P_a - 1) I_A + P_c I_C - (P_b - 1) I_B\right]$$

$$= \frac{1}{3}\left(I_A + I_B + I_C\right)$$

$$= I_S^0 \tag{5.44}$$

This relationship is further illustrated in Figure 5.22. By inspection it can be seen that the sum of the primary currents is equal to three times the secondary zero sequence current.

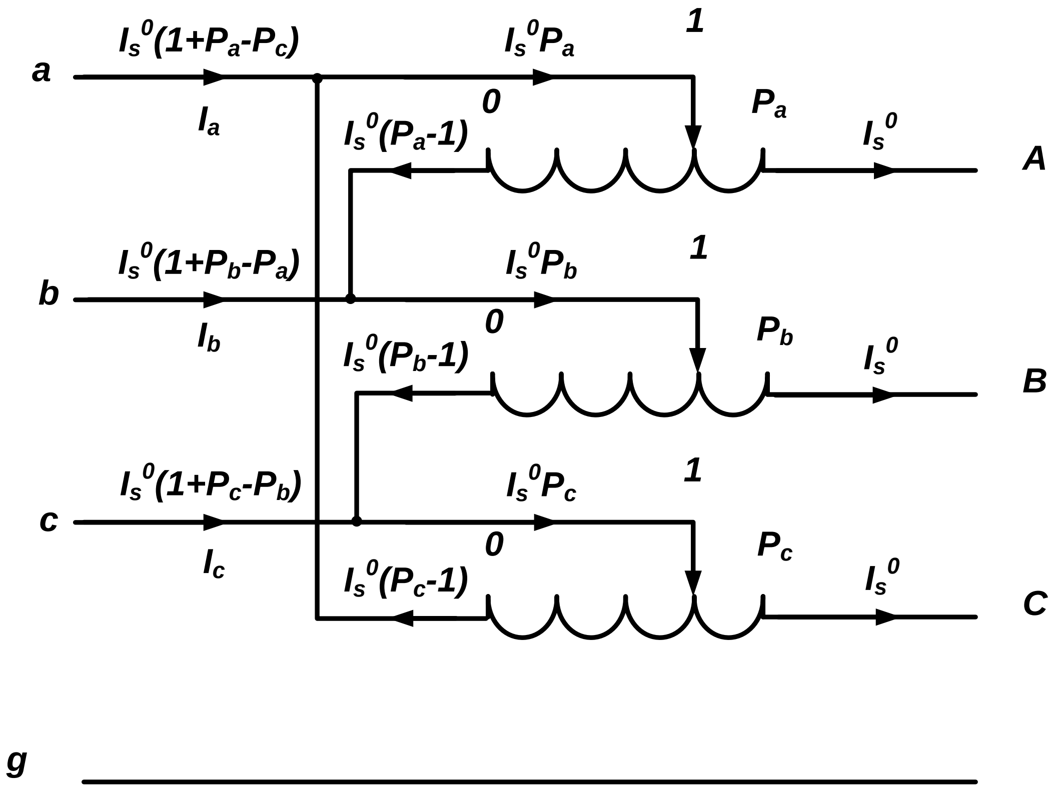


Figure 5.22. Zero sequence currents in a three delta connected auto-transformer voltage regulator.

Let I_P^+ and I_S^+ be the primary and secondary positive sequence currents respectively.

By definition:

$$I_P^+ = \frac{1}{3}\left(I_a + aI_b + a^2 I_c\right) \tag{5.45}$$

From (5.40), (5.41), (5.42) and (5.45) we get:

$$I_P^+ = \frac{1}{3}\left[P_a I_A - P_c I_C + I_C + a\left(P_b I_B - P_a I_A + I_A\right) + a^2\left(P_c I_C - P_b I_B + I_B\right)\right] \tag{5.46}$$

Let us consider the case where $P_b = P_c = P_{bc}$

Then from (5.46) we get:

$$I_P^+ = \frac{1}{3}\left[P_a I_A - P_{bc} I_C + I_C + aP_{bc} I_B - aP_a I_A + aI_A + a^2 P_{bc} I_C - a^2 P_{bc} I_B + a^2 I_B\right]$$

$$= \frac{1}{3}\left[(1-a)\left(P_{bc} I_A + aP_{bc} I_B + a^2 P_{bc} I_C\right) + (1-a) I_A\left(P_a - P_{bc}\right) + a\left(I_A + aI_B + a^2 I_C\right)\right] \tag{5.47}$$

But:

$$I_S^+ = \frac{1}{3}\left(I_A + aI_B + a^2 I_B\right) \tag{5.48}$$

and:

$$I_A = I^0 + I^+ + I^- \tag{5.49}$$

From (5.47), (5.48) and (5.49) we get:

$$I_P^+ = I_S^+\left[P_{bc} - a(P_{bc} - 1)\right] + \frac{1-a}{3}\left(I_S^0 + I_S^+ + I_S^-\right)\left(P_a - P_{bc}\right) \tag{5.50}$$

Similarly where I_P^- and I_S^- be the primary and secondary negative sequence currents respectively:

$$I_P^- = I_S^-\left[P_{bc} - a^2(P_{bc} - 1)\right] + \frac{1-a^2}{3}\left(I_S^0 + I_S^+ + I_S^-\right)\left(P_a - P_{bc}\right) \tag{5.51}$$

Equation (5.44) and Figure 5.22 show that under all auto-transformer ratio conditions, there is a zero sequence current path through the in-line voltage regulator. These equations also show that, if the auto-transformer ratios are not equal the zero sequence current on the secondary side will cause some positive and negative sequence currents to flow in the primary side of the voltage regulator. Provided there is no significant impediment to the primary positive and negative sequence currents, there will not be any significant impedance to the flow of zero sequence currents through the voltage regulator when the auto-transformer ratios are not identical. This means that, even if the ratios are not identical at the time of a line to earth fault on the system, this in-line voltage regulation arrangement will not impede the proper operation of the arc suppression coil.

Based on Figures 5.19 and 5.20 for ideal transformers, the voltage relationships can be expressed as follows:

$$V_{Ag} = V_{ag} + V_{ab}(P_a - 1) \tag{5.52}$$

$$V_{Bg} = V_{bg} + V_{bc}(P_b - 1) \tag{5.53}$$

$$V_{Cg} = V_{cg} + V_{ca}(P_c - 1) \tag{5.54}$$

From (5.52) we get:

$$V_{Ag} = V_{ag} + (V_{ag} - V_{bg})(P_a - 1)$$

$$V_{Ag} = V_{ag}P_a - V_{bg}(P_a - 1) \tag{5.55}$$

From (5.53) we get:

$$V_{Bg} = V_{bg} + (V_{bg} - V_{cg})(P_b - 1)$$

$$V_{Bg} = V_{bg}P_b - V_{cg}(P_b - 1) \tag{5.56}$$

From (5.54) we get:

$$V_{Cg} = V_{cg} + (V_{cg} - V_{ag})(P_c - 1)$$

$$V_{Cg} = V_{cg}P_c - V_{ag}(P_c - 1) \tag{5.57}$$

Let V_P^+, V_P^- and V_P^0 be the positive, negative and zero sequence primary voltages respectively.

Let V_S^+, V_S^- and V_S^0 be the positive, negative and zero sequence secondary voltages respectively.

By definition:

$$V_S^0 = \frac{1}{3}\left(V_{Ag} + V_{Bg} + V_{Cg}\right) \tag{5.58}$$

Then from (5.55), (5.56), (5.57) and (5.58) we get:

$$V_S^0 = \frac{1}{3}\Big[V_{ag}P_a - V_{bg}(P_a - 1) + V_{bg}P_b - V_{cg}(P_b - 1) + V_{cg}P_c - V_{ag}(P_c - 1)\Big]$$

$$\begin{aligned} &= \frac{1}{3}\left(V_{ag} + V_{bg} + V_{cg}\right) \\ &+ \frac{1}{3}\Big[V_{ag}(P_a - P_c) + V_{bg} + V_{bg}(P_b - P_a) + V_{cg}(P_c - P_b)\Big] \end{aligned} \tag{5.59}$$

However:

$$V_P^0 = \frac{1}{3}\left(V_{ag} + V_{bg} + V_{cg}\right) \tag{5.60}$$

Then from (5.59) and (5.60) we get:

$$V_S^0 = V_P^0 + \frac{1}{3}\Big[V_{ag}(P_a - P_c) + V_{bg}(P_b - P_a) + V_{cg}(P_c - P_b)\Big] \tag{5.61}$$

Let us consider the case where $P_a = P_c = P_{ac}$

Then from (5.61) we get:

$$V_S^0 = V_P^0 + \frac{P_{ac} - P_b}{3}\left(V_{cg} - V_{bg}\right) \tag{5.62}$$

However:

$$\begin{pmatrix} V_{ag} \\ V_{bg} \\ V_{cg} \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix} . \begin{pmatrix} V_P^0 \\ V_P^+ \\ V_P^- \end{pmatrix} \tag{5.63}$$

Therefore from (5.62) and (5.63) we have:

$$V_S^0 = V_P^0 + \frac{P_{ac} - P_b}{3}\Big[(a - a^2)V_P^+ + (a^2 - a)V_P^-\Big]$$

$$= V_P^0 - j\,\frac{P_b - P_{ac}}{\sqrt{3}}\left(V_P^+ - V_P^-\right) \tag{5.64}$$

Equation (5.64) is illustrated in Figure 5.23.

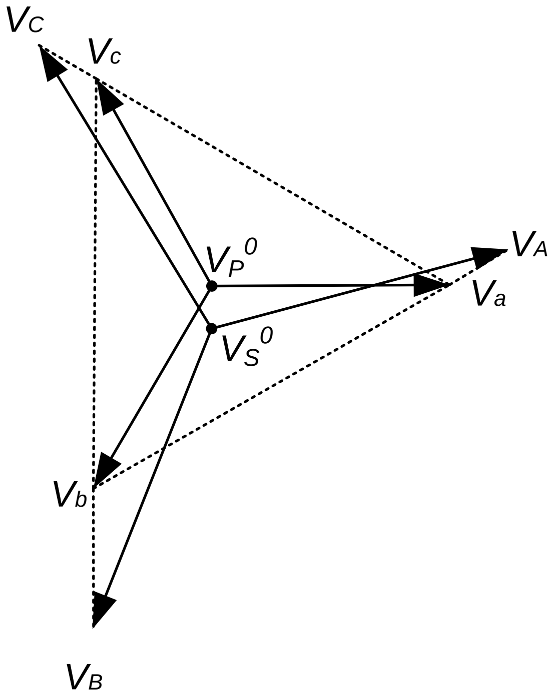


Figure 5.23 Phasor diagram for a three delta connected auto-transformer voltage regulator with P_b greater than P_a and P_c.

$$V_S^+ = \frac{1}{3}\left(V_{Ag} + aV_{Bg} + a^2V_{Cg}\right) \tag{5.65}$$

Then from (5.55), (5.56), (5.57) and (5.65) we get:

$$V_S^+ = \frac{1}{3}\left[V_{ag}P_a - V_{bg}(P_a - 1) + aV_{bg}P_b - aV_{cg}(P_b - 1) + a^2V_{cg}P_c - a^2V_{ag}(P_c - 1)\right] \tag{5.66}$$

Let us consider the case where P_a=P_b=P_c=P

Then from (5.66) we get:

$$V_S^+ = \frac{1}{3}\left[P\left(V_{ag} + aV_{bg} + a^2V_{cg}\right) - \left(P - 1\right)a^2\left(V_{ag} + aV_{bg} + a^2V_{cg}\right)\right] \tag{5.67}$$

But:

$$V_P^+ = \frac{1}{3}\left(V_{ag} + aV_{bg} + a^2V_{cg}\right) \tag{5.68}$$

Therefore from (5.67) and (5.68) we have:

$$V_S^+ = V_P^+\left[P - a^2(P-1)\right]$$

$$= V_P^+\left[1 + \left(1 - a^2\right)\left(P-1\right)\right] \tag{5.69}$$

But by definition:

$$a^2 = -0.5 - j\,{\sqrt{3}}\!\big/\!{2} \tag{5.70}$$

Therefore from (5.69) and (5.70) we have:

$$V_S^+ = V_P^+\left[1 + \left(1.5 + j\,{\sqrt{3}}\!\big/\!{2}\right)\left(P-1\right)\right] \tag{5.71}$$

Therefore:

$$\left|V_S^+\right| = V_P^+\sqrt{1 + 3\left(P-1\right) + 2.25\left(P-1\right)^2 + 0.75\left(P-1\right)^2}$$

$$= V_P^+\sqrt{1 + 3\left(P-1\right) + 3\left(P-1\right)^2} \tag{5.72}$$

An evaluation of equation (5.72) shows that the voltage boost provided by three delta auto- transformers provides approximately 1.5 times the voltage boost of each of the individual auto-transformers. This is further illustrated in Figure 5.24 and 5.25. These calculations were checked by using the EMTP software.

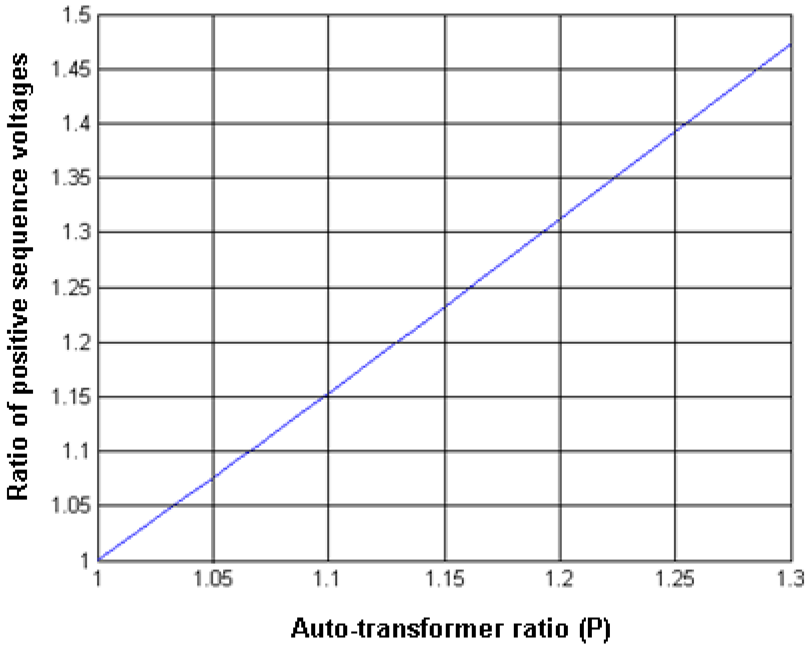


Figure 5.24 Positive sequence voltage ratio provided by three delta connected auto-transformers.

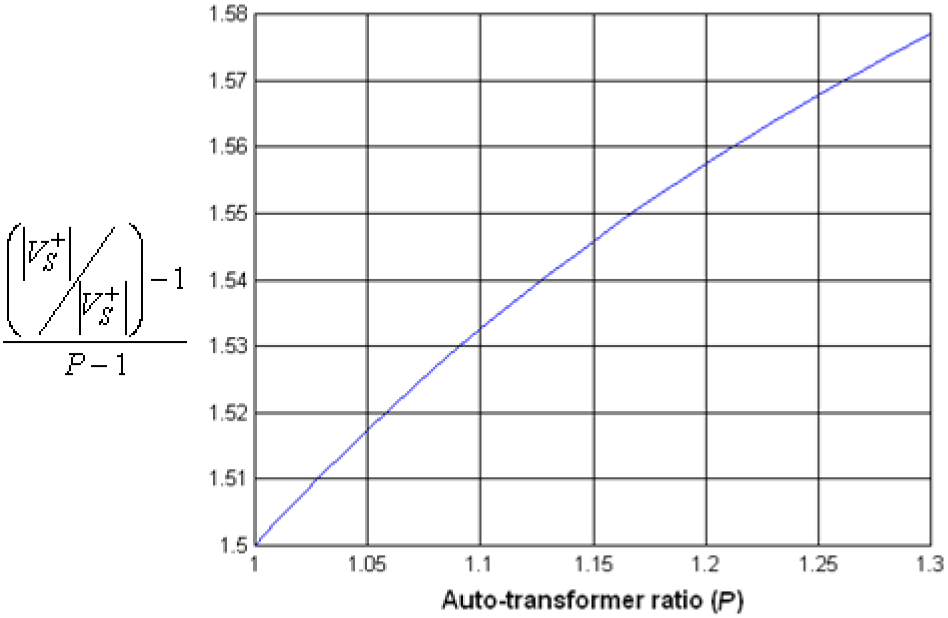


Figure 5.25 Positive sequence voltage boost provided by three delta connected auto-transformers as a ratio of the voltage boost of each individual auto-transformer.

5.3.2 Analysis of a simple system with delta connected auto-transformers

Let us consider a simple system consisting of a single radial high voltage distribution line supplied by a delta-star transformer with the star point earthed through a tuned arc suppression line and a three auto-transformer voltage regulator situated M km from the source and N km before the end of the length of the line as shown in Figure 5.26.

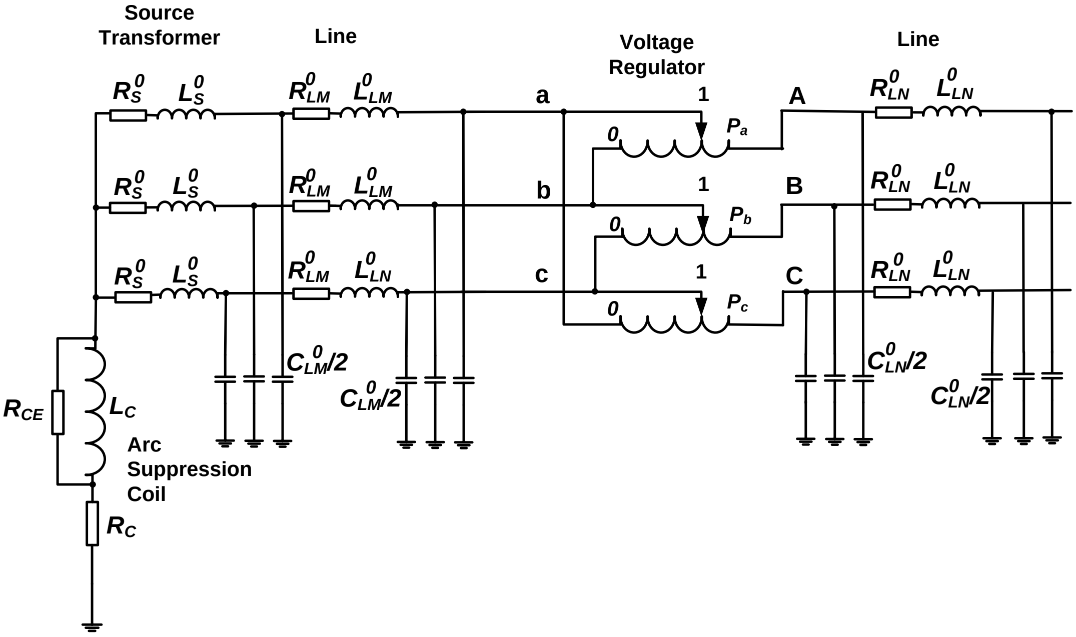


Figure 5.26 Three delta connected auto-transformers in a simple 11 kV system showing zero sequence and earthing components.

The arc suppression coil is tuned to the system capacitance to earth such that:

$$3\omega L_C = \frac{1}{\omega\left(C_{LM}^0 + C_{LN}^0\right)} \tag{5.73}$$

If P_a, P_b and P_c are not equal the line to earth voltages are no longer equal in magnitude the line to earth capacitive currents will no longer add to zero. Current will therefore flow through the earthing inductor. As the inductance of the earthing coil is cancelled by the line to earth capacitances the magnitude of current will only be limited by the resistance in the circuit and saturation of the magnetic core of the earthing inductor. This can result in neutral voltage displacement and corresponding over-voltages in one or more of the phases. Depending on the system configuration the voltages can be high enough to cause insulation failures.

The zero sequence symmetrical components can be used to analyse the over-voltages. The effect of the three delta connected auto-transformers is to increase the positive sequence voltage. If the three auto-transformer ratios are not identical they will introduce a zero sequence voltage change. As the positive and negative sequence impedances have negligible effect they have been ignored in this analysis.

In accordance with equations 5.44 and 5.64 the zero sequence network then resolves to that shown in Figure 5.27.

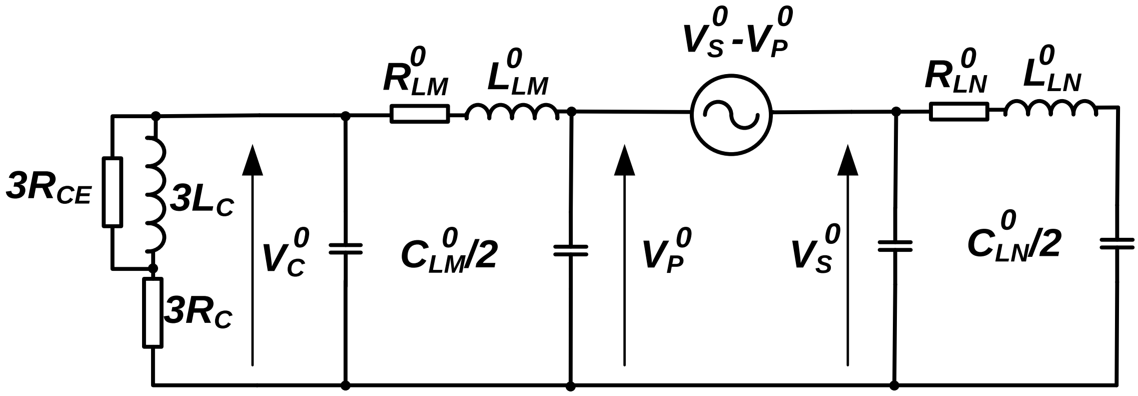


Figure 5.27 Zero sequence network of the simple system.

The following parameter values were assumed.

Voltage regulator ratios;

$P_a = P_c = P_{ac} = 1.1$

$P_b - P_{ac} = 0.0125$

This corresponds with a single tap position for many voltage regulators.

Line *M* zero sequence resistance values; $R_{LM}^0 = 10\ \Omega$

Line *N* zero sequence resistance values; $R_{LN}^0 = 15\ \Omega$

Line *M* zero sequence inductance, $L_{LM}^0 = 100\,\text{mH}$

Line *M* zero sequence inductance, $L_{LN}^0 = 150\,\text{mH}$

Line *M* zero sequence capacitance, $C_{LM}^0 = 0.085\ \mu\text{F}$

Line N zero sequence capacitance, $C_{LN}^{0} = 0.1275$ μF

From (5.18) the arc suppression coil inductance $L_C = 15.8935\,\mathrm{H}$

The arc suppression coil was assumed to have 2% series resistance and 2% magnetising resistance as follows:

Arc suppression coil resistance $R_C = 0.02\omega L_C$

Arc suppression coil magnetising resistance $R_{CE} = \dfrac{\omega L_C}{0.02}$

From (5.64):

$$V_S^0 - V_P^0 = j\,\frac{P_{ac} - P_b}{\sqrt{3}} V_P^{+} = j0.00722 \text{ pu}$$

Analysis of the zero sequence network gives V_C^0, the neutral voltage at the source transformer, as 0.107 pu. or 679 volts in an 11 kV system. For a 10 % variation in tap setting the neutral voltage becomes 0.856 pu. or 5,436 volts in an 11 kV system. The three phase system was then analysed using the EMTP software as shown in Figure 5.28 and the corresponding neutral voltages were almost identical to those calculated from the above zero sequence calculations, thus confirming the sequence analysis and calculation.

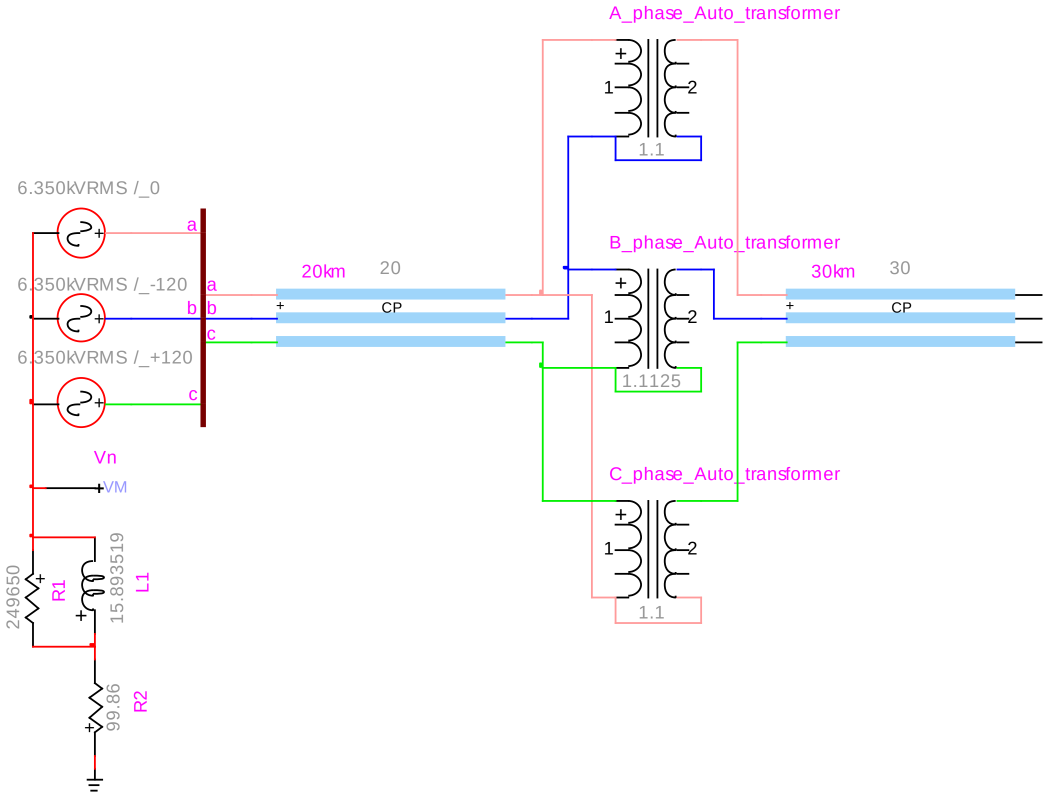


Figure 5.28 EMTP representation of three single phase delta connected auto-transformers in the simple system.

If the system is slightly detuned and/or a saturable magnetic core is used for the earthing inductor the voltages will be lower but can still reach significant values. However detuning the inductor increases the fault current and reduces the sensitivity to high impedance earth faults.

For a three delta connected auto-transformer type voltage regulator with one of the transformers out of voltage ratio and a perfectly tuned arc suppression coil system the phase angle of the neutral voltage will depend on which of the transformers is out of ratio and whether the ratio is high or low.

This system, as shown in Figure 5.5, was then analysed, with each auto-transformer in turn out of ratio by plus 10%, and the proportion of the network on the load side of the regulator continuously varying from 0% to 100%. The resulting neutral voltages were plotted as shown in Figure 5.29.

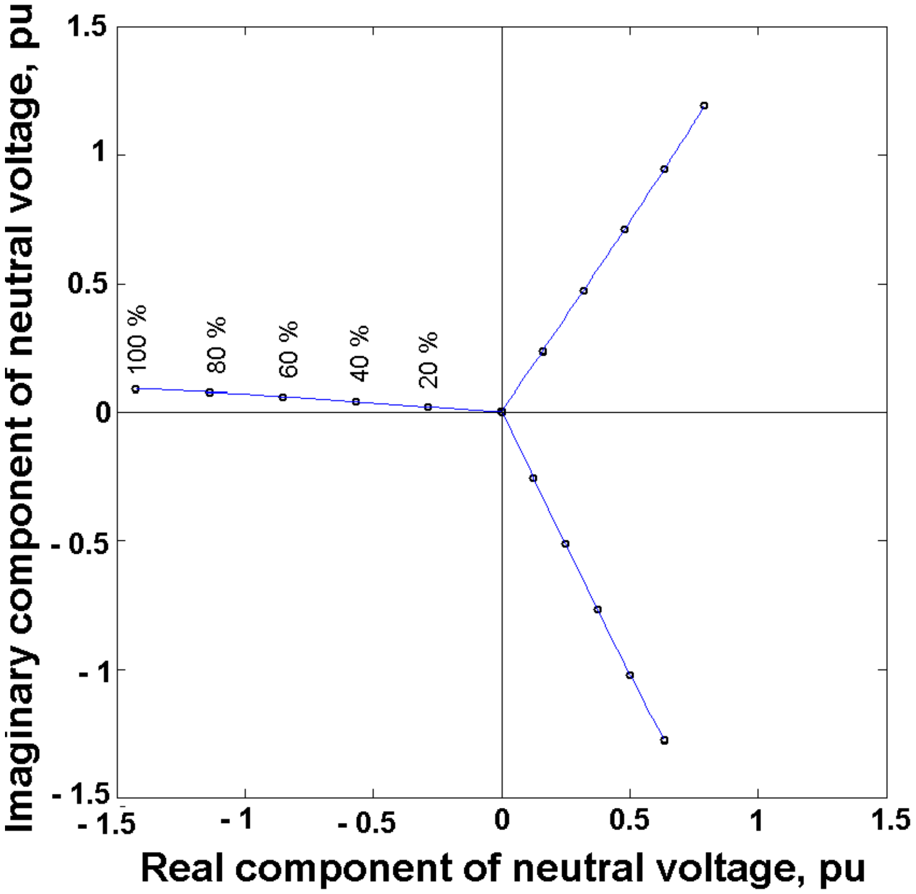


Figure 5.29 Neutral voltage, for each auto-transformer in turn out of ratio by plus 10 %, and the portion of the network on the load side of the regulator varying continuously from 0 % to 100 %.

The neutral voltage displacement shown in Figure 5.29 is close to that shown in Figure 4.5 for a single line to earth fault. The type of fault can be distinguished, to some extent, by the magnitude of the neutral voltage. In the case of a low impedance line single line to earth fault, the neutral voltage will be close to 1 pu. In the case of an auto-transformer being out of step, the neutral voltage will increase gradually as the tap changing mechanism operates. The increased voltage will therefore be detected well before it reaches 1 pu. However, it may not be possible to distinguish between a developing high impedance single line to earth fault and an out of step auto-transformer on the basis of the neutral voltage magnitude and phase angle alone. The solution is to arrange for an alarm to be sent from each in-line voltage regulator when an out of step condition arises. This can conveniently be transmitted by means of a radio link, a simple radio transmitter, or by an alarm sent over the mobile phone network.

The logic diagrams for the substation protection system as shown in Figure 4.22 and Figure 4.23 would then be modified to those shown in Figure 5.30 and Figure 5.31 respectively.

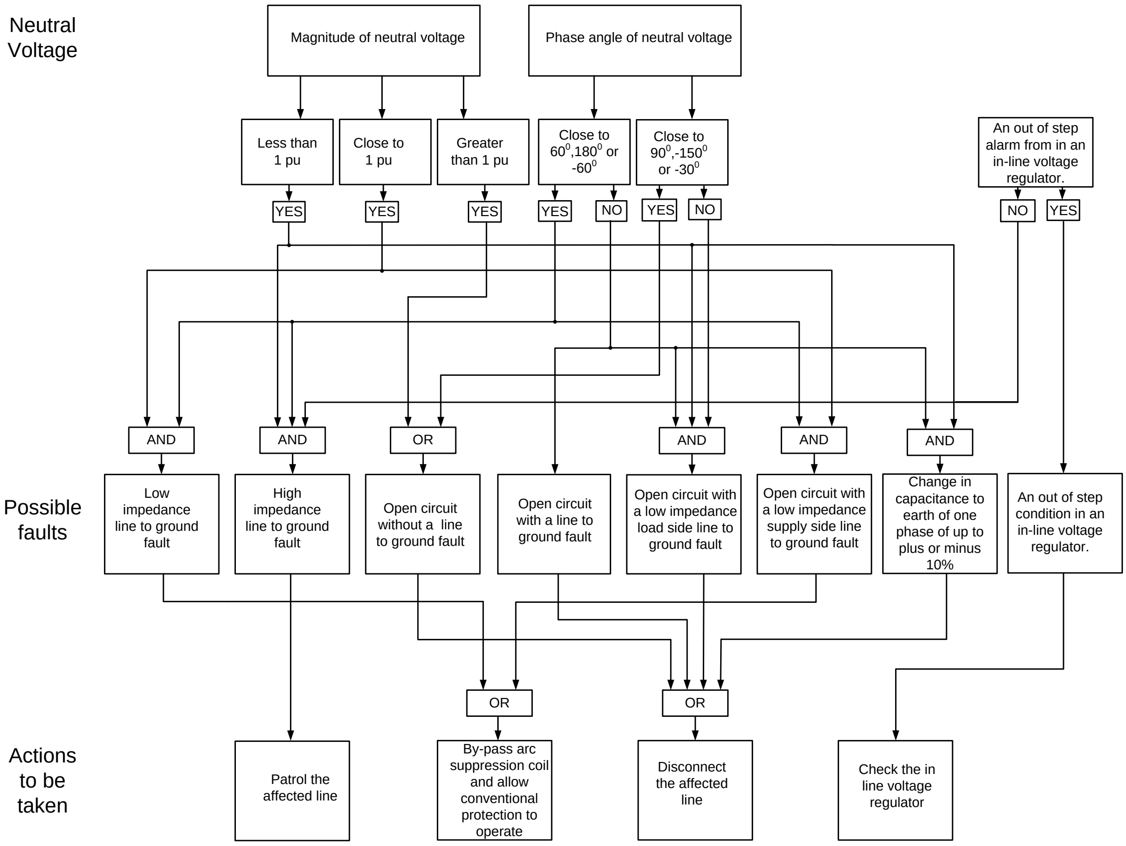


Figure 5.30 Possible fault types and appropriate actions deduced from the neutral voltage and in-line voltage regulator alarms.

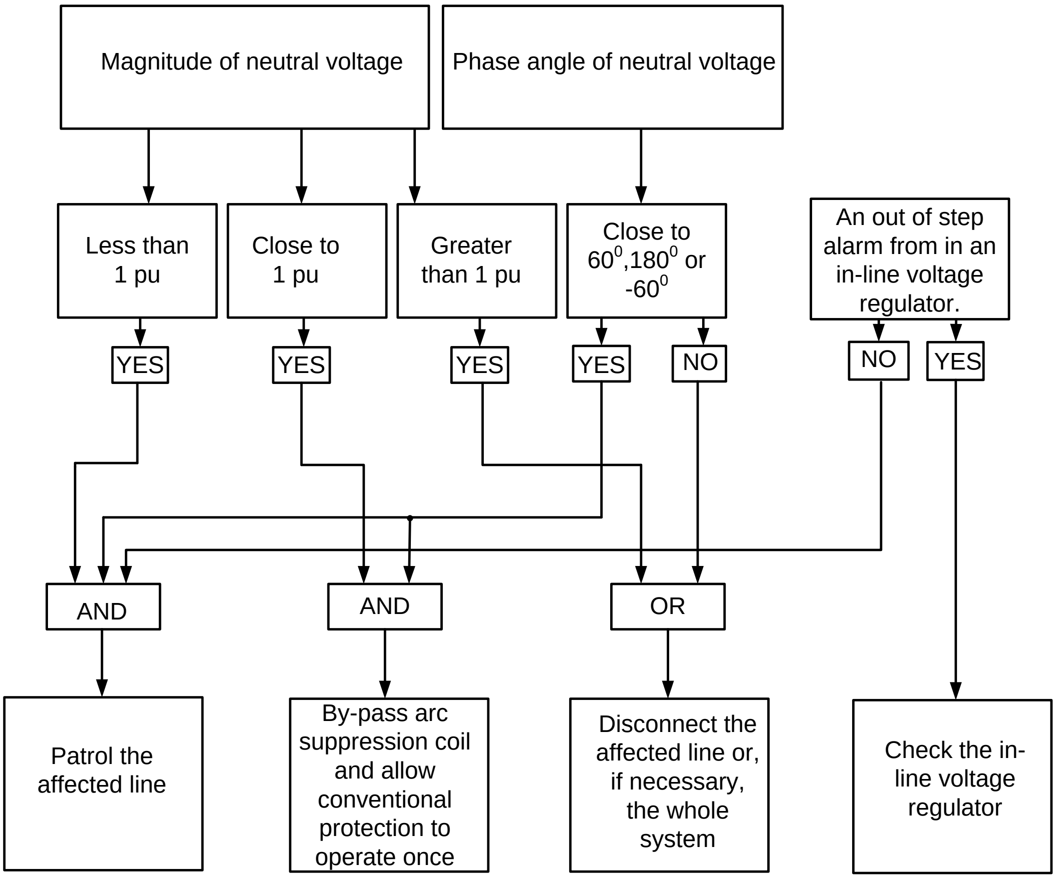


Figure 5.31 Logic for taking action on the basis of the neutral voltage and in-line voltage regulator alarms.

5.4 Static VAR compensation

The voltage level along the high voltage distribution may also be boosted by the use of static VAR compensation. When capacitors are connected between the lines the capacitive current flowing through the inductive lines causes an increase in the voltage at the location of the capacitors. The usual method of connecting these capacitors is on the low voltage side of a delta-star step down transformer. They will therefore not provide a zero sequence path to earth and will not reduce the effectiveness of the arc suppression coil system. Several small installations of static VAR compensators may provide an economic means of voltage regulation along the lines and so reduce the number of in-line voltage regulators needed. It has been shown in [65] that several of these units can successfully regulate the voltage. The overall arrangement of in-line regulators and static VAR compensators will need to be determined on a case by case basis.

5.5 Summary

Open-delta voltage regulators are now widely used to provide in-line voltage regulation for rural high voltage distribution feeders instead of the more expensive ground type three phase auto-transformers.

5.5.1 Results from modelling of open-delta voltage regulators

A method of representing open-delta voltage regulators by symmetrical components has been developed.

If arc suppression coils are used on power systems which also incorporate open-delta voltage regulators, dangerous voltages can occur under normal system conditions. Although the level of the over-voltages is reduced by the use of earthing inductors having a saturable magnetic core, voltages in excess of the rated insulation levels will still occur. Therefore open-delta voltage regulators should not be used in power systems fitted with arc suppression coils.

5.5.2 Results from modelling of three star connected auto-transformers.

It has been shown that when star connected auto-transformers are used to provide in-line voltage regulation and the star point is not earthed there is no zero sequence conductivity through the arrangement apart from the transformer energising currents. For optimum operation of arc suppression coil systems it is necessary for there to be relatively high zero sequence conductivity along all of the lines. If the star point is earthed, the optimum tuning inductance of the arc suppression coil will change every time the auto-transformer ratios change. Therefore it is not appropriate to use star connected auto-transformers to providing in-line voltage regulation in arc suppression coil equipped power systems.

5.5.3 Results from modelling of three delta connected auto-transformers.

Three single phase delta connected auto-transformers can be used satisfactorily to provide three phase in-line voltage regulation in power systems with arc suppression coils provided arrangements are made to keep the auto-transformer ratios in step. An out of step ratio of about 1.25% for short periods, such is as normal during tap changes, will cause only a small neutral voltage which is acceptable. If, for any reason, the auto-transformer ratio difference becomes large the resulting voltages may not be acceptable. If a line to earth fault occurs at a time when the auto-transformer ratios are out of step, the zero sequence currents will still flow through the in-line voltage regulator allowing the arc suppression coil system to operate correctly.

The neutral voltage resulting from an out of step auto-transformer may be similar to that from a high impedance line to earth fault. By utilising an alarm from the in-line voltage regulator, it is possible to take the correct action automatically if either a high impedance line earth fault or an out of step condition exists.

The voltage boost provided by three delta auto- transformers provides approximately 1.5 times the voltage boost of each of the individual auto-transformers. This can be understood by examination of Figure 5.20 or equation (5.72).

5.5.4 Results for static VAR compensation

Distributed static VAR compensators may also be used to provide in-line voltage regulation. The overall arrangement of static VAR compensators and in-line voltage regulators needs to be decided on a case by case basis.

5.5.5 Summary of results for in-line voltage regulators

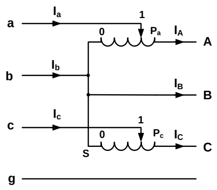
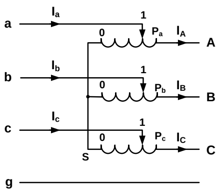
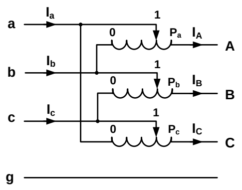
For the successful operation of arc suppression coil systems, in-line voltage regulators need to meet two essential criteria:

1. Under normal conditions they must not introduce a zero sequence voltage.

2. They must not impede the flow of zero sequence current.

Table 5.1 summarises three methods of providing in-line voltage regulation in terms of these criteria.

Table 5.1 Summary of in-line voltage regulator connections in terms of criteria for successful arc suppression coil operation

	Two Open Delta Connected Auto-Transformers	**Three Star Connected Auto-Transformers**	**Three Delta Connected Auto-Transformers**
			
Causes high neutral voltages during normal operation	YES	NO	Only if the auto-transformer ratios are not close to identical
Inhibits the flow of zero sequence currents	NO	YES	NO

It can be seen that the delta connected auto-transformer arrangement meets the above criteria**.**

Although three star connected auto-transformers can be used, the arc suppression coil ideal tuning inductance value would change depending on the ratios of the auto-transformers and they would still need to withstand the full line to line voltage during a line to earth fault. They have no advantage over the use of the three delta connected auto-transformers.

Distributed static VAR compensation can also be used to maintain voltage along the high voltage radial line.

Chapter 6 MINIMISING CROSS COUNTRY FAULTS

When a line to earth fault occurs in a high voltage power system with an arc suppression coil there is an increase in the voltages to earth of the two healthy phase lines. The fault event can be associated with a step voltage injection triggered by the fault occurrence that excites the various propagation modes of the multi-conductor lines comprising the network and results in a complex high frequency electromagnetic transient. The wave shape of the transient depends on the input impedances of components connected to the line terminations. Depending on the timing of the fault, the addition of the transient voltages to the displaced voltages of the healthy phase lines can cause over-voltages that will, in some cases, cause insulation failure on the otherwise healthy phase lines [51-54]. There are then two phase to earth faults often on remote parts of the system. The arc suppression system cannot compensate for either of these faults. These cross country faults can cause disconnection of two separate lines. The phenomenon of these transient voltages adding to the displaced voltage and thus increasing the strain on the insulation of the healthy phases has long been recognized [51]. Experience has shown that there is likely to be an increased incidence of simultaneous faults when arc suppression coil systems are used [52-54]. The writer has personal experience of an arc suppression coil system in a 66 kV sub-transmission system in Queensland, Australia being permanently taken out of service because of the incidence of cross country faults. This history has contributed to reluctance by electricity supply authorities to install arc suppression coil systems in Australia.

Existing systems that have been operated with effectively earthed neutrals for many years will have components which, while they can safely withstand the normal line to earth voltage, will not withstand the over-voltages at the time of a line to earth fault when the system is not effectively earthed. In Australia, and in many other countries, transmission and distribution systems are effectively earthed. There is renewed interest in arc suppression coil systems due to increasing public pressure to improve the safety and continuity of supply and because of recent developments in the arc extinguishing properties of modern systems. If proper account is not taken of the transient over-voltages either trial installations will be a failure and all work will stop or trial installations will not proceed because of the uncertainties surrounding the incidence of cross country faults.

The likely magnitudes of these over-voltages are analysed in detail and the implications for existing power systems discussed. Simple methods for estimating the approximate magnitudes, frequency and durations of the transient voltages are given.

A method of replicating the transient over-voltages in a high voltage test facility is suggested and a new method of controlling these over-voltages is proposed. Testing of power system components and control of transient over-voltages are discussed as complementary strategies to minimise cross country faults.

6.1 A radial line without any branches

Consider the simple system shown in Figure 6.1

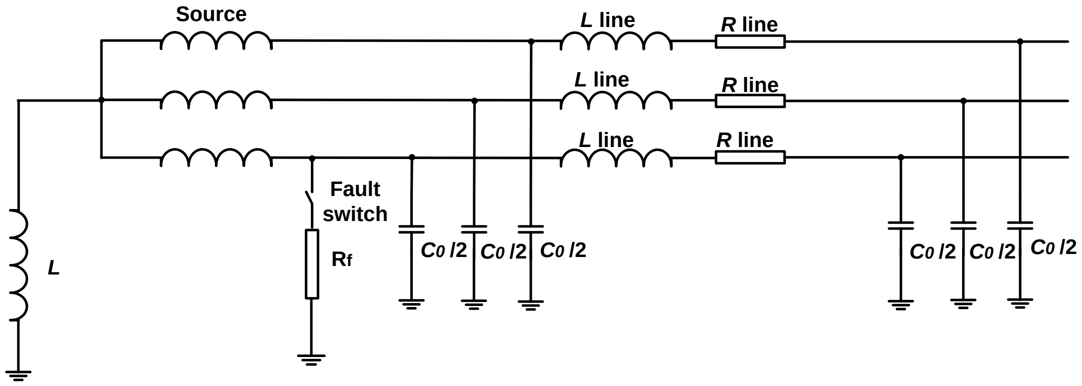


Figure 6.1 Simple 11 kV System showing zero sequence and earthing components.

A single length of line is supplied by the star winding of a transformer. The transformer neutral is earthed through an inductor tuned to the total system line to earth capacitance. As an aid to the understanding of the transient phenomena the line is simplified to show the distributed line to earth capacitances as combined into lumped capacitances at each end of the line. The practical distributed capacitance case is analysed later. Consider an earth fault near the transformer with a fault resistance of $R_{f.}$

The symmetrical component representation of the system is as shown in Figure 6.2.

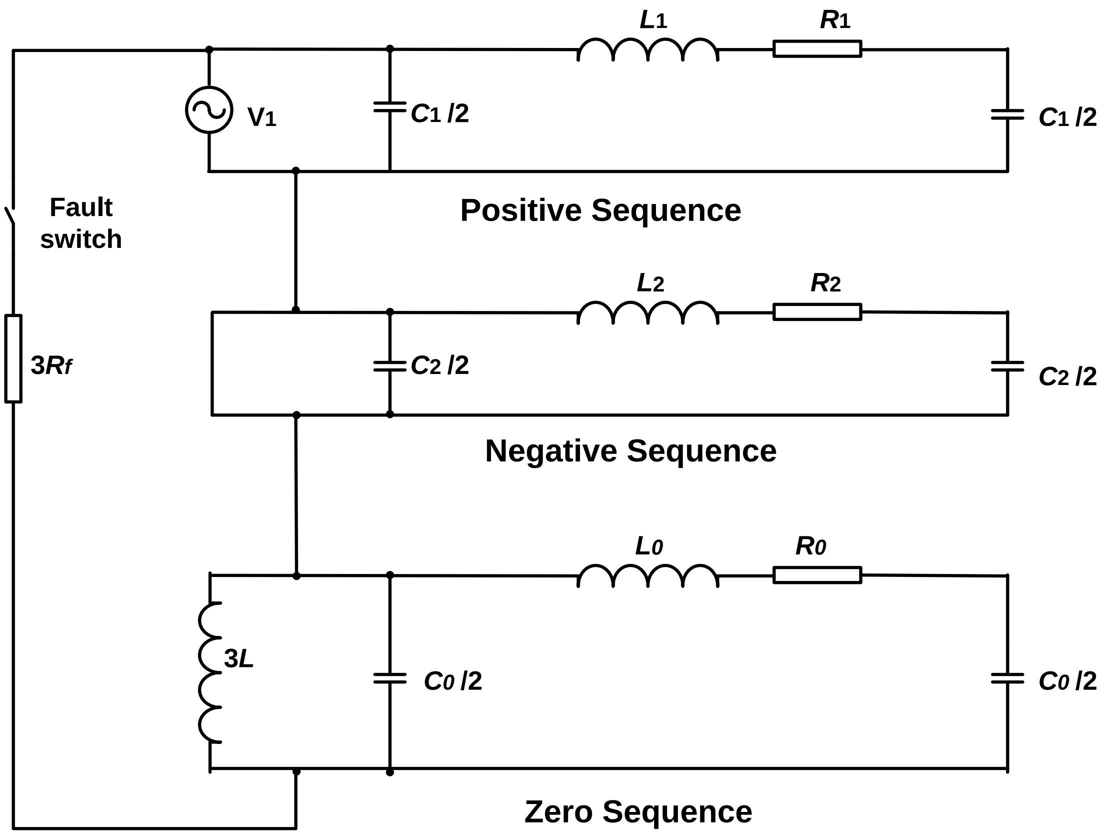


Figure 6.2 Symmetrical network representation of the simple system.

Whilst this is not a general analysis, it is still valuable as it allows a physical understanding of the phenomena involved. The maximum voltage, the frequency of oscillation and the decay time can be estimated.

6.1.1 The worst case scenario for the peak voltages

If the source impedances are ignored and the fault is at the source, the transient voltages and currents will be predominantly of the common mode type affecting each of the phase conductors in an identical manner. The zero sequence network can then be used to analyse the transient voltages and currents.

At the instant the fault is applied, provided the voltage of the faulted line is not zero, a step voltage will be applied across the zero sequence network at the fault point. The resultant current will flow to charge the line to earth capacitance of the far section of the line and oscillation in voltage and current will follow until it decays because of the effect of the resistances.

There are then three voltages being applied to the far end of the lines.

1. The positive sequence fundamental frequency voltage,

2. The zero sequence fundamental frequency voltage, and
3. A transient voltage alternating at the natural frequency of the line zero sequence inductance and capacitance and decaying to zero.

Depending on the time of the fault in the fundamental frequency cycle, these voltage transients may cause serious over-voltages on the healthy lines.

The positive and negative sequence source impedances can be ignored in this analysis because we are analysing a worst case scenario. Any source impedance will have the effect of reducing the magnitude of the step voltage change across the zero sequence network. Analysis using ElectroMagnetic Transients Program (EMTP) software has confirmed that, if realistic supply transformer impedances are used and the impedances are adjusted to typical values as seen by the transient currents, there will be a slight decrease in the maximum value of the peak transient voltage.

Although the zero sequence diagram shows the line capacitances lumped at the ends of the line, the analysis presented in this section is also applicable to a distributed model.

In the case of distributed capacitances and a perfect system without any resistance either in the line or in the earth plane a step transient current/voltage wave will travel to the end of all three lines and be reflected back to the fault point. It will travel back and forth setting up a square wave oscillation. In a practical system with some resistance the magnitude will decay. Because the resistances as seen by the higher frequency components of the square wave are much higher than the resistances as seen by the major frequency of the square wave, the wave shape of the oscillation will closely approximate a sine waveform within a few cycles. The main frequency, magnitude and decay time will be close to but not quite equal to that given by the simplifying assumption of capacitances lumped at the ends of the line.

Consider a low impedance fault to earth on the ‘A’ phase at a time ‘t_f’ such that;

$$\theta = \omega t_f \tag{6.1}$$

Let the phase voltages at the source just before the occurrence of the fault be;

$$E_a = E \sin \omega t_f^- \tag{6.2}$$

$$E_b = E \sin(\omega t_f^- - 120^0) \tag{6.3}$$

$$E_c = E \sin(\omega t_f^- + 120^0) \tag{6.4}$$

Ignoring voltage drops due to load, the steady state voltages at the fault point with the fault in place will be:

$$E^{+} = E\sin\omega t \qquad (6.5)$$

$$E^{-} = 0 \qquad (6.6)$$

$$E_{0} = -E\sin\omega t \qquad (6.7)$$

The line voltages at the fault point will then be;

$$E_{fa} = E^{+} + E^{-} + E^{0}$$

$$= E\sin\omega t - E\sin\omega t = 0 \qquad (6.8)$$

$$E_{fb} = a^{2}E_{1} + aE_{2} + E_{0}$$

$$= E\sin(\omega t - 120^{0}) - E\sin\omega t \qquad (6.9)$$

$$E_{fc} = aE^{+} + a^{2}E^{-} + E^{0}$$

$$= E\sin(\omega t + 120^{0}) - E\sin\omega t \qquad (6.10)$$

Neglecting the small changes in voltage as a result of the load currents and the line capacitive currents, these steady state voltages will appear at both ends of the line.

In other words, at the instant of the fault all of the line to earth voltages at the source will change by $-E\sin\theta$. A current/voltage wave will travel to the end of the line. When it reaches the end, the voltages on each phase line at the far end will change by $-2E\sin\theta$. Let δt be the time taken for a current/voltage wave to travel from the fault point to the end of the line. The voltages at the end of each phase line when the transient pulse arrives will be:

$$E_{ea}(t+\delta t) = E\sin(\theta + \omega\delta t) - 2E\sin\theta \qquad (6.11)$$

$$E_{eb}(t+\delta t) = E\sin(\theta + \omega\delta t - 120^{0}) - 2E\sin\theta$$

$$= E\begin{bmatrix} -0.5\sin\theta\cos\omega\delta t - 0.5\cos\theta\sin\omega\delta t \\ -0.866\cos\theta\cos\omega\delta t + 0.866\sin\theta\sin\omega\delta t - 2\sin\theta \end{bmatrix} \qquad (6.12)$$

$$E_{ec}(t+\delta t) = E\sin(\theta+\omega\delta t+120^0) - 2E\sin\theta$$

$$= E\begin{bmatrix} -0.5\sin\theta\cos\omega\delta t - 0.5\cos\theta\sin\omega\delta t \\ +0.866\cos\theta\cos\omega\delta t - 0.866\sin\theta\sin\omega\delta t - 2\sin\theta \end{bmatrix} \qquad (6.13)$$

However, for short transmission lines, as $\omega\delta t$ is very small, $\cos\omega\delta t$ will be very close to unity and $\sin\omega\delta t$ will be very close to zero.

Therefore $E_{eb}(t+\delta t) \approx \mathrm{E}\left[-0.5\ \sin\theta\ \text{-}\ 0.866\ \cos\theta\ \text{-}\ 2\ \sin\theta\right]$

$$\approx -\mathrm{E}\left[2.645\ \sin(\theta+19.11^0)\right] \qquad (6.14)$$

$$E_{ec}(t+\delta t) \approx E\left[-0.5\ \sin\theta\ +\ 0.866\ \cos\theta\ -\ 2\ \sin\theta\right]$$

$$\approx -E\left[2.645\ \sin(\theta-19.11^0)\right] \qquad (6.15)$$

The four worst case scenarios are for a fault at a time such that

$$\theta = \pm 90^0 \pm 19.11^0 \qquad (6.16)$$

In these cases the peak voltage will be 2.645 pu.

Allowing for the time taken for the wave to reach the far end of the line the maximum value will be slightly higher. The value depends on the length of the line and the relative phase angles of the voltages at each end of the line. The absolute maximum is such that the fault occurs at the time of maximum voltage on the faulted phase and reaches the open end of the line at the time of maximum voltage on one of the healthy phases. In this case, by examination of equations (6.11) to (6.13), the maximum transient voltage will be 3 pu. If the line length between the fault location and the end of the line is such that $\omega\delta t = 60^0$, then substituting into equation (13) gives:

$$E_{ec}(t+\delta t) = -3E\sin\theta \qquad (6.17)$$

For this to occur, in the case of a purely air insulated overhead line and allowing for the partial conductivity of the earth plane, the length would be approximately 850 km. For lines of this length it is usual that there will be a significant difference in the phase of the voltages at either end. There will also be significant attenuation of the wave because of the time taken. Therefore, for long lines, the likely transient voltages can only be analysed on an individual case by case basis for particular loading conditions.

6.1.2 Estimation of frequency and decay time for a typical 11 kV overhead line type.

A single line system, consisting of 20 km of 11 kV three phase 7/3.75 AAC overhead line with flat construction and supplied by the star winding of a transformer, was modelled. The transformer neutral was earthed through a tuned arc suppression coil with negligible resistance.

The line inductance and resistance parameters are affected by the higher frequency of the transient currents.

The zero sequence line to earth capacitance is given by the well known formula:

$$C_0 = \frac{2\pi k}{3Ln\left(\frac{4H}{GMD}\right)} \quad F/m \tag{6.18}$$

where:

$H =$ The conductor height

$GMD =$ The Geometric Mean Diameter of the conductor configuration as a bundle for zero sequence representation.

$k = 8.85 \times 10^{-12}$ F/m

For the 20 km length of line where $GMD = 469mm$ and $H = 9m$:

$C_0 = 0.0854\ \mu F$

As a first approximation of the transient frequency of oscillations, the time taken for the current/voltage wave to travel to the end of the line and return was taken as half a cycle. The method proposed by Gatous and Pissolato [55] to allow for the skin effect, and the well known complex depth of return method as reiterated by Wang and Liu [56] were used to calculate R_0 and L_0, for this frequency. Using these values the frequency of oscillation for the simple model with lumped capacitances was revised using the formula:

$$\text{Frequency in radians per second} = \frac{\sqrt{8L_0C_0 - R_0^2C_0^2}}{2L_0C_0} \tag{6.19}$$

New values for R_0 and L_0 were then found.

By successive iterations it was found that;

R_0 = 161.1 Ω

L_0 = 77.98 mH

Frequency = 2803 Hz

The time constant for the decay of the oscillations was calculated using equation (6.20).

$$\text{Time constant in seconds } = \frac{2L_0}{R_0} \tag{6.20}$$

$$= 0.968 \, ms$$

Using the ElectroMagnetic Transients Program (EMTP) software a frequency dependent 11 kV line with the above physical characteristics simulated and the resulting time constant was almost identical. The EMTP frequency dependent line model is based on the work by J. Marti [57].

The EMTP software was also used to check the calculation of the line capacitance. A simulated 1 Hz zero sequence voltage was applied to both ends of a half kilometre of the above 11 kV line type. By reading the capacitive current, the zero sequence capacitance (C^0) was found for a 20 km length of line to be 0.0857 µF

The EMTP software was also used to check the calculation of the line inductance and resistance. A three phase to earth zero impedance fault at one end of a half kilometre of the above 11 kV line type was simulated and a 2,803 Hz zero sequence sine wave source was applied to the other. By measuring the current magnitude and phase angle the line parameters were found to be:

R_0 = 153.5 Ω

L_0 = 76.88 mH

Allowing for the approximations inherent in the methods used to find the parameters for the EMTP line representation, these values confirm the calculations.

The 20 km single line model was analysed using the EMTP software. A phase to earth fault was applied to phase C near the source and the voltages appearing at the end of the line as calculated by EMTP are shown in Figure 6.3.

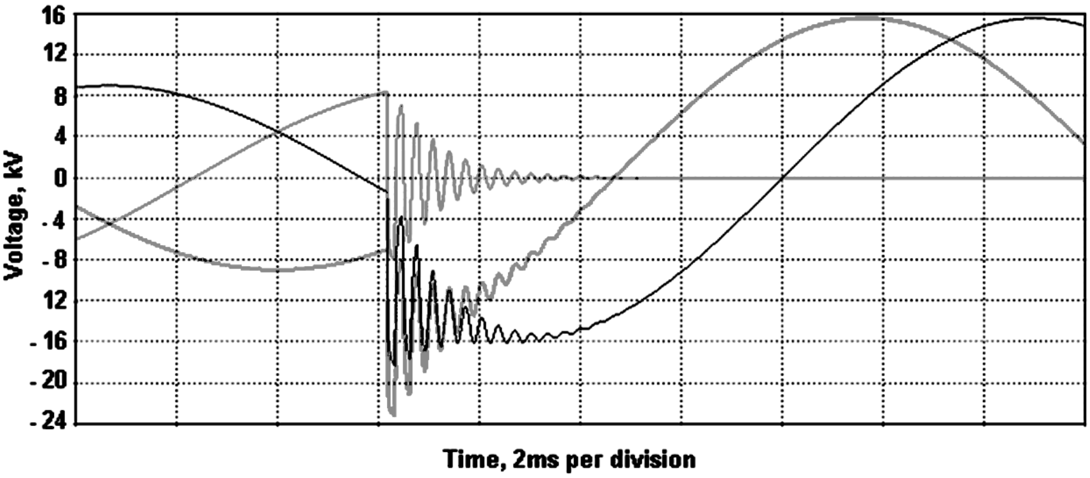


Figure 6.3 Transient voltages for the single line model as shown by EMTP.

It can be seen that the peak voltage on a healthy phase line is 23.2 kV which is 2.58 pu.

Frequency = 3082 *Hz*

Time constant of decay = approximately 1 *ms*

These values from the distributed capacitance line model are within 10% of those calculated using lumped capacitances.

The single line model was replicated by a physical model with resistors and reactors chosen to accurately represent the zero sequence line impedances as seen by the high frequency oscillating currents but with a safe voltage applied. The major difference was that, whereas the EMTP model used distributed line capacitance, the physical model used capacitances lumped at the ends of the lines. As shown in Figure 6.4 the transient voltages were similar to those shown by the EMTP model.

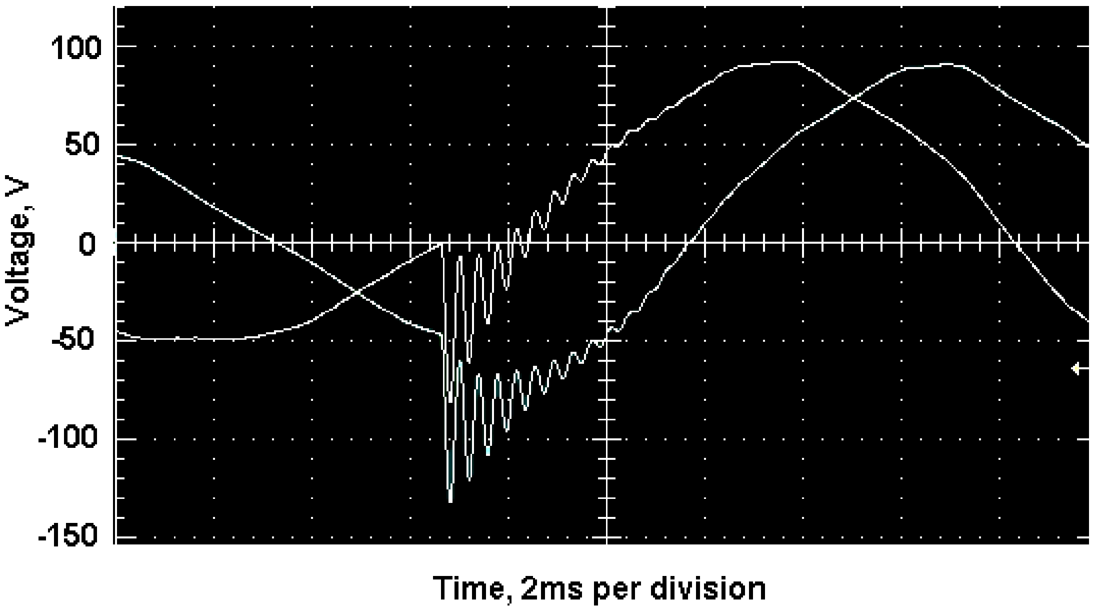


Figure 6.4 Transient voltages on the un-faulted phase lines of the physical model.

Both the EMTP simulation and the physical model used a full three phase system and not symmetrical components. The close agreement validates the assumption that the voltage and current transients under consideration are predominantly of the common mode or zero sequence type. A close study of Figure 6.4 shows the frequency of oscillation to be very close to 2803 Hz with a time constant of decay close to 1 ms as calculated using the zero sequence network. In both cases the line to earth capacitance is lumped at the ends of the line. The slightly higher frequency given by the EMTP model is as a result of correctly representing the line to earth capacitances as distributed along the line.

6.1.3 Approximate methods for transient voltage estimation

The maximum transient voltage in a non-effectively earthed system will be 3 pu.

The time taken for a current\voltage wave to travel from the fault point to the end of an overhead line and return can be determined approximately. Ignoring the effects of insulators and the proximity to the conductive earth plane, the current/time wave will travel at the speed of light that is approximately $3x10^8$ metres per second. However the EMTP analysis in this paper shows that for a practical 11 kV overhead system, with a partially conductive earth plane, the speed will be reduced by a factor of 0.82. The calculations in [66] for a 345 kV line give a factor of 0.87. For a first approximation a factor of 0.85 would give sufficient accuracy. For more detailed analysis a full simulation using EMTP or other software would be appropriate. This time will correspond to half a cycle of the transient oscillation.

Therefore:

$$\text{Frequency} = \frac{2.55\text{x}10^8}{4D}\,Hz \tag{6.21}$$

Where D is the total line distance in metres.

The time constant for the decay of these oscillations is given by equation (6.20).

The values of L_0 and R_0 are frequency dependent. As the frequency increases, L_0 decreases and R_0 increases. As we are interested in the worst case scenario we need only estimate the time constant for the minimum oscillating frequency that relates to the longest length of line.

The method proposed by Gatous and Pissolato [55] to allow for the skin effect, and the complex depth of return method as reiterated by Wang and Liu [56], together with equation (6.20) were used to calculate the time constants for the decay of the transient oscillations for a range of all aluminium conductors and a typical 11 kV overhead line construction as shown in Figure 6.5.

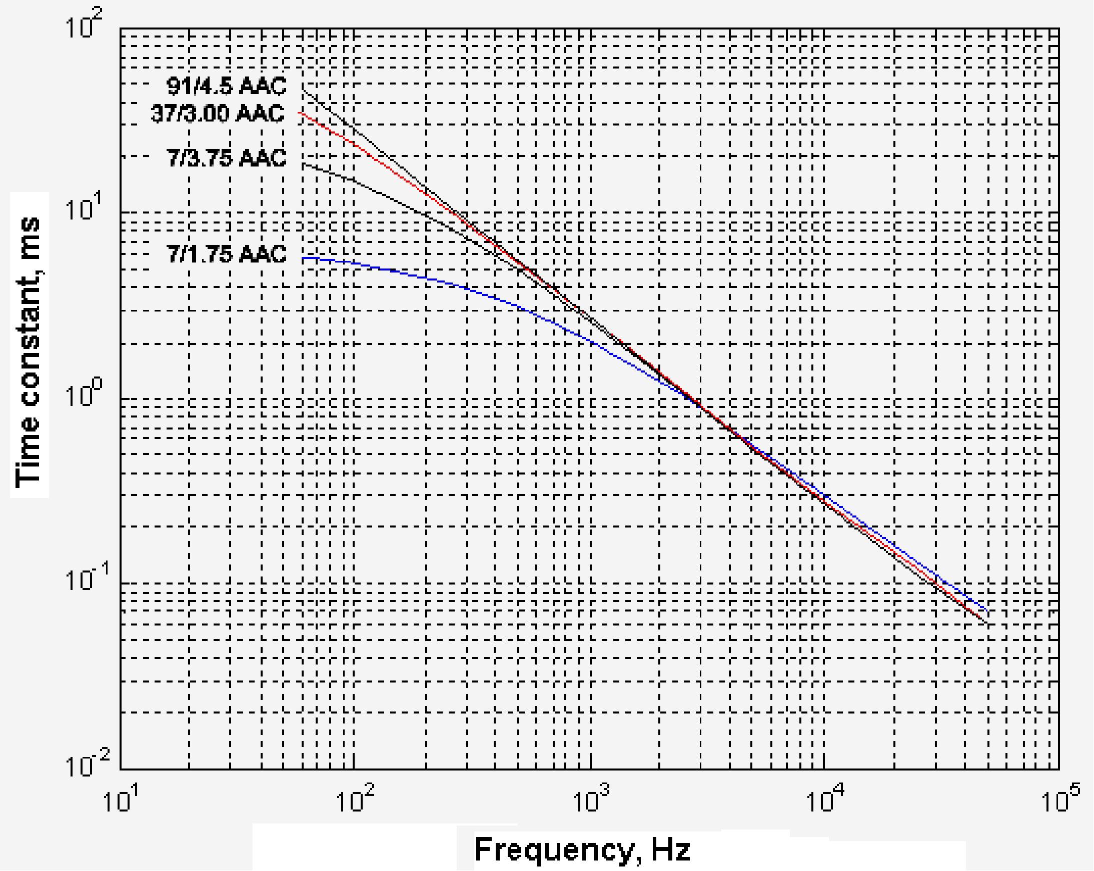


Figure 6.5 Time constants for the decay in transient oscillations for typical 11 kV overhead line construction.

It is noted that for large conductors there is close to an inverse logarithmic relationship between the decay time constant and the frequency.

This is further illustrated in Figure 6.6 that shows the transient decay time constant in term of the number of cycles of the transient oscillation.

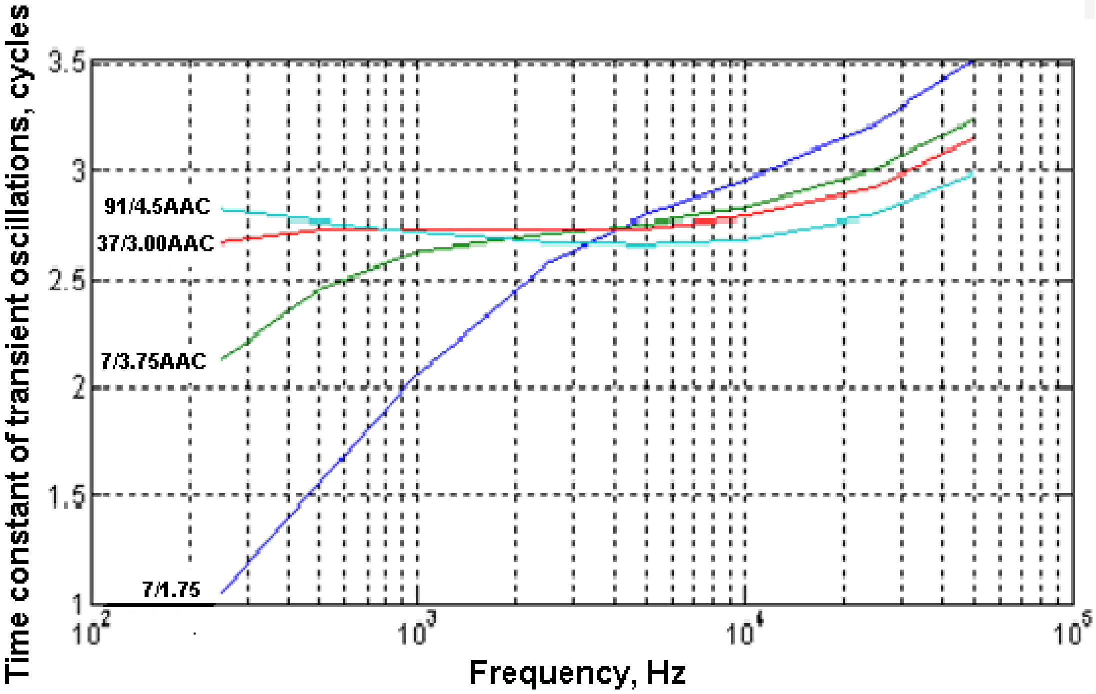


Figure 6.6 Time constants for the decay in transient oscillations for a typical 11 kV overhead line construction in cycles of the transient oscillations.

6.2 Typical zone substation distribution systems

The above analysis is based on a single radial line without any branches or distribution transformers. As evaluated in Appendix 2, the distribution transformers connected to the system will contribute some zero sequence capacitance. In cases where there are branch lines and transformers, the interaction of the transient steps becomes more complex. At each discontinuity the transient voltage will reduce according to the relative surge impedances of the outgoing conducting paths. Despite this reduction, there are circumstances where two or more of these transient voltages can coincide and reinforce each other. In some situations they can add together to give a peak voltage slightly higher than the maximum values for a single line. For example in the case of a 40 km typical 7/3.75 AAC 11 kV overhead line with a 10 km spur line mid way along there can be a peak transient voltage of up to 2.713 pu. Without the spur line the corresponding peak transient voltage is 2.630 pu.

To evaluate transient over voltage effects on power distribution systems realistic urban and rural zone substation distribution system models were analysed using EMTP software.

The typical urban zone substation distribution system model is a shown in Figure 6.7.

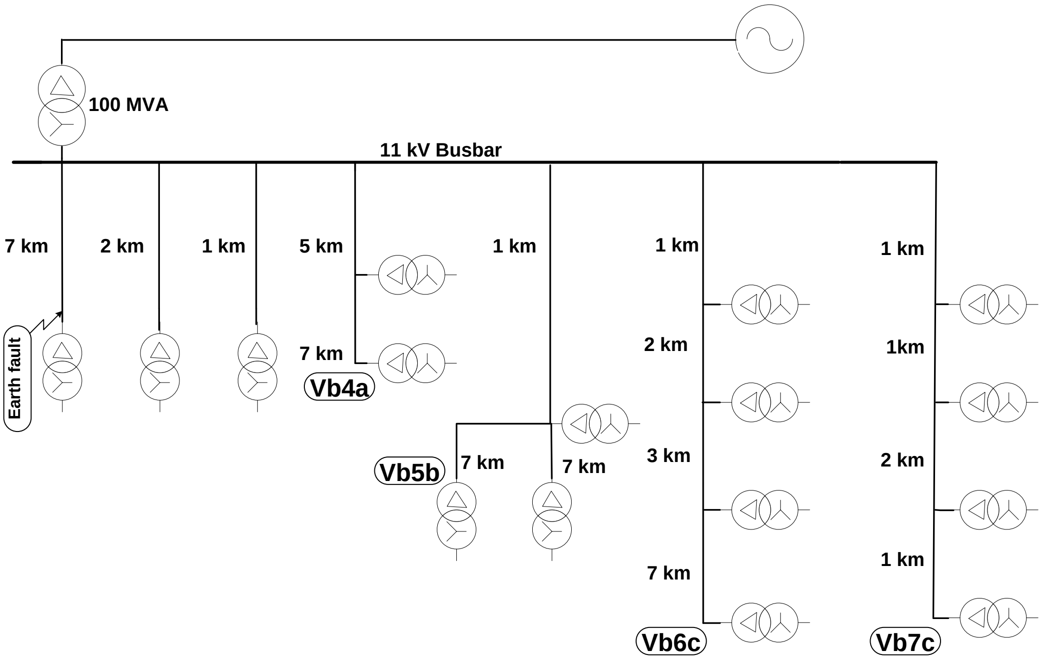


Figure 6.7 Urban zone substation distribution system.

Using EMTP software and with a tuned arc suppression coil, a phase to earth fault at a point 7 km from the bus bar was simulated. The transient voltages recorded at the far ends of the four longest feeders were as shown in Figure 6.8. The highest transient voltage peak was 2.69 pu.

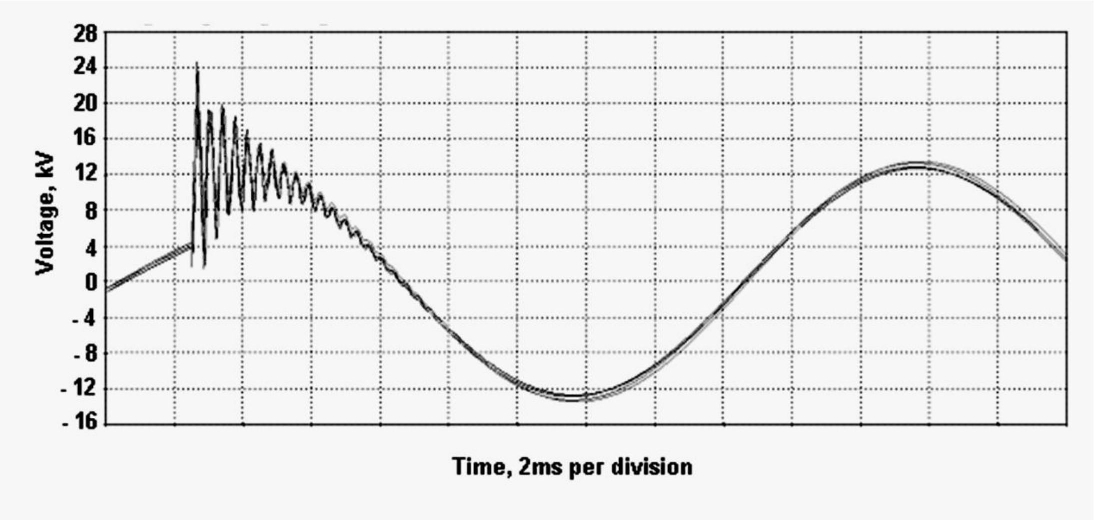


Figure 6.8 Transient voltages on a healthy phase of the urban distribution system.

The typical rural zone substation distribution system model is as shown in Figure 6.9.

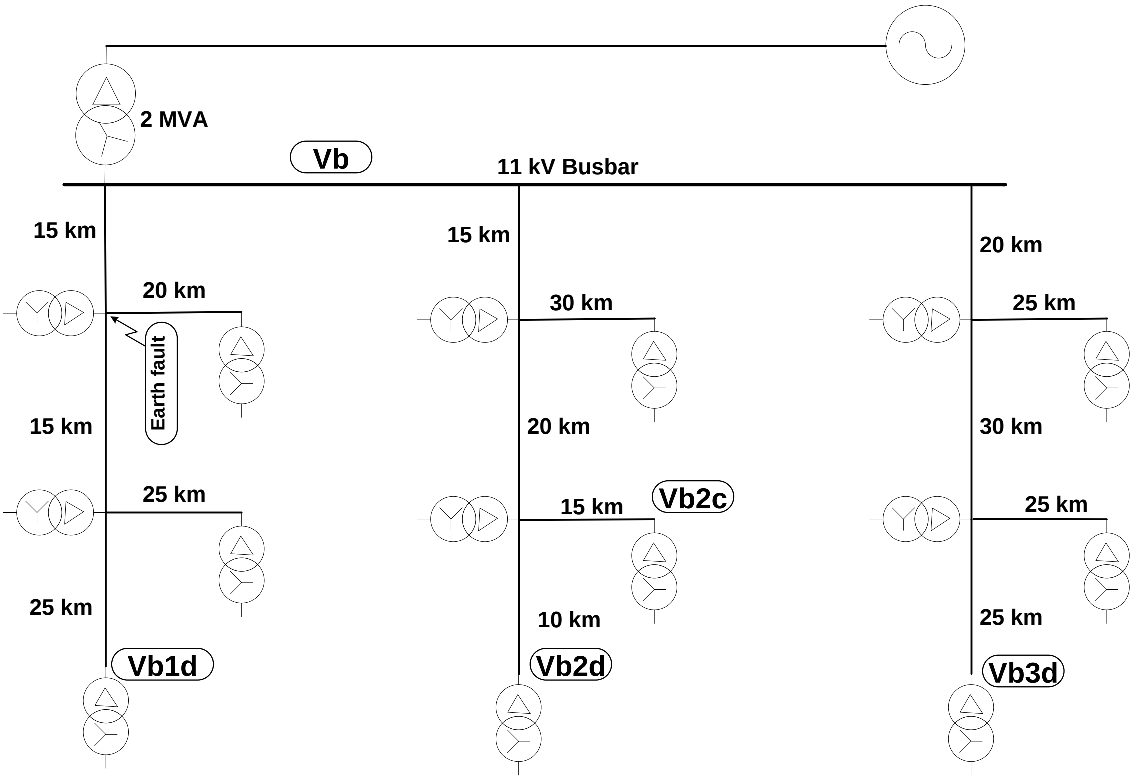


Figure 6.9 Rural zone substation distribution system.

Using the EMTP software and with an arc suppression coil, a phase to earth fault at a point 15 km from the bus bar was simulated. The transient voltages recorded on some of the points on the system were as shown in Figure 6.10.

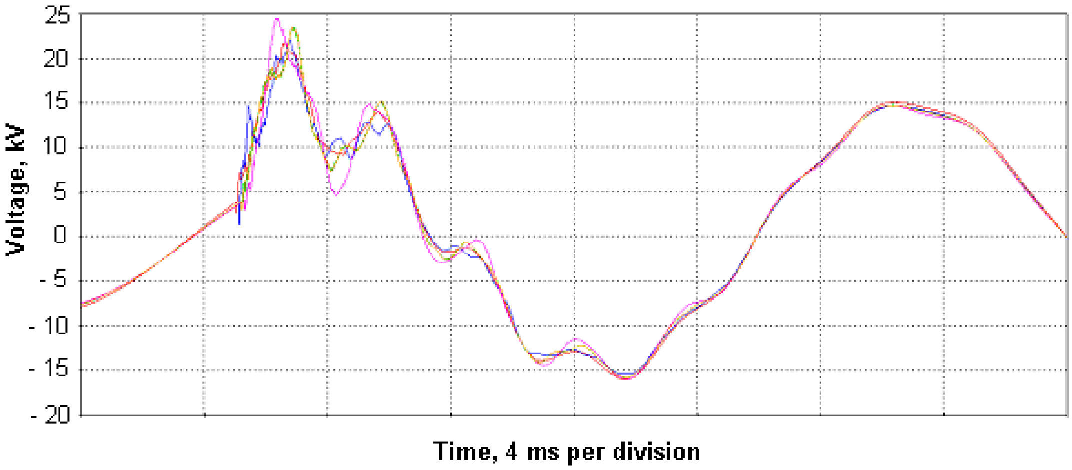


Figure 6.10 Transient voltages on a healthy phase of the rural distribution system.

It can be seen that, as there are relatively long lengths of line and multiple branches, there are transient oscillations at multiple frequencies.

The tuning of the arc suppression coil has little effect on these transient voltages. Provided the transformer neutral is not effectively earthed, transient voltages will occur.

6.3 Implications for existing systems

Where all of the equipment in service complies with the standard insulation levels set out in Table 2 or Table 3 of AS 1824.1 [67], which is based on IEC 71-1 (1993), these transient over-voltages will not cause a cross country fault. In practice there are many high voltage distribution systems with components that have not been manufactured to meet current standards and that have not been tested to the current standards. There are also likely to be many components that have deteriorated to the extent that, while they can still withstand 1.0 pu voltage with a safety margin, they will not withstand these transient over-voltages. It may not be feasibly to upgrade all components in the system.

Similarly metal oxide surge arrestors suitably rated at 1.732 pu and in specified working order will not reach a thermal run away condition with short duration 3 pu voltages. However, in many high voltage systems there are likely to be surge arrestors which have deteriorated to the extent that they will allow arcing and power follow currents to flow resulting in cross country faults.

The implications for existing high voltage distribution systems can be determined by removing samples of the insulators and surge arrestors for withstand voltage tests using waveforms similar to these transient voltage waveforms. An economic way of carrying out this type of analysis initially may be to test all apparently healthy components removed from service for other reasons. The percentage failure of the components that are tested will provide a good indication off the likelihood of cross country faults.

6.4 Testing of system components

The system shown in Figure 6.11 was set up in a high voltage testing facility to illustrate one simple method of testing the ability of power system components to withstand the transient over-voltages.

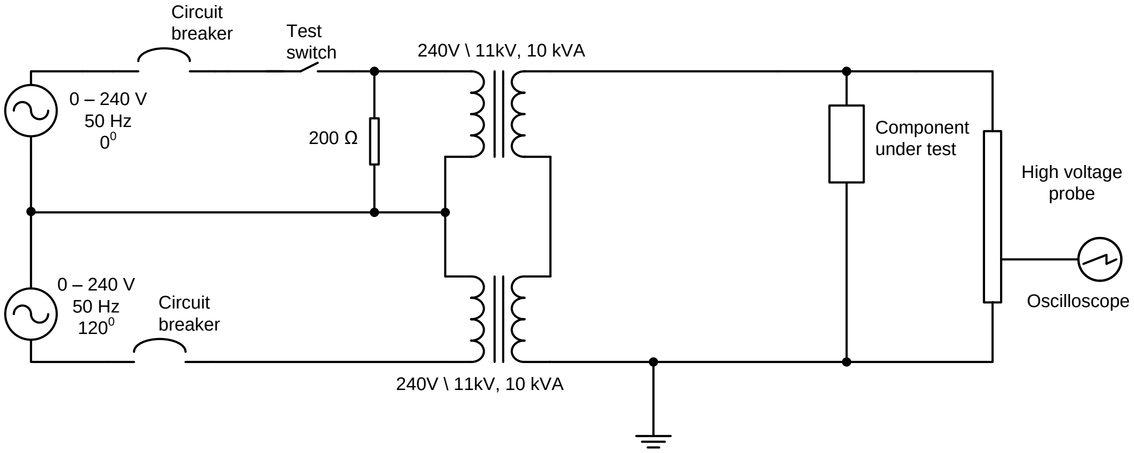


Figure 6.11 Arrangement for testing network system components.

The input voltages were adjusted to provide the steady state voltages of the power system. The test transformers were found to have adequate leakage inductance, shunt capacitance and resistance. The resultant test voltage waveform was typical of that to be found in practice. No attempt was made to synchronise the closing of the test switch with the input voltage waveform. The test switch was closed and opened several times and the resulting voltages recorded. In a practical test system, point of wave switching can be arranged so that the worst case scenario is replicated for each test. A sample of the voltage applied to the component under test is shown in Figure 6.12.

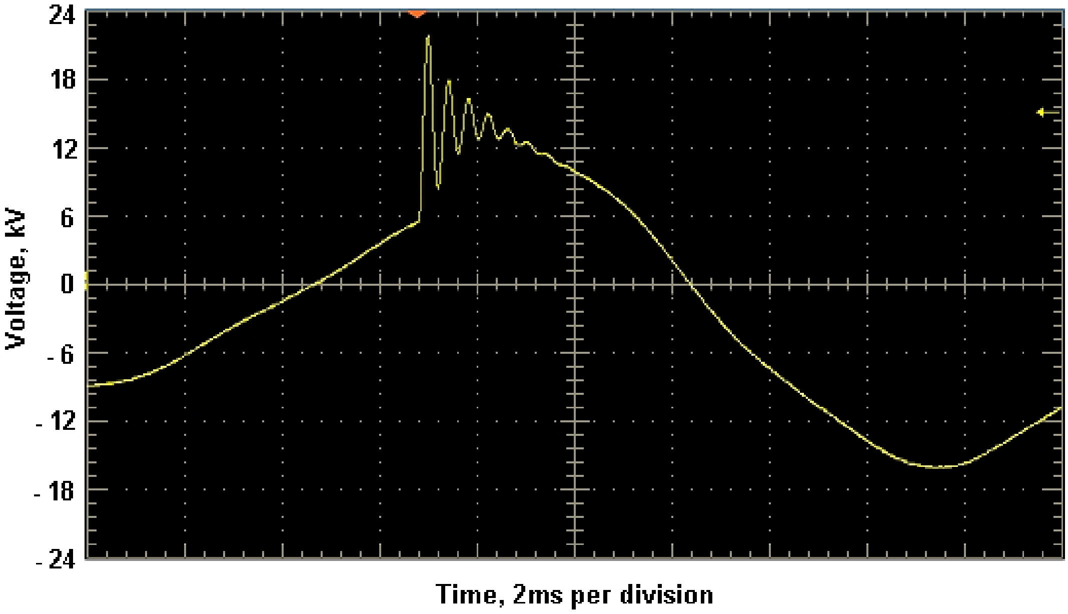


Figure 6.12 Test voltage applied to power system components.

6.5 Proposed method of controlling transient over-voltages

A new method has been developed for controlling the transient over-voltages. A bipolar thyristor bank is connected in parallel with the arc suppression coil to effectively earth the neutral of the supply transformer from the time of the fault to the first current zero as shown in Figure 6.13.

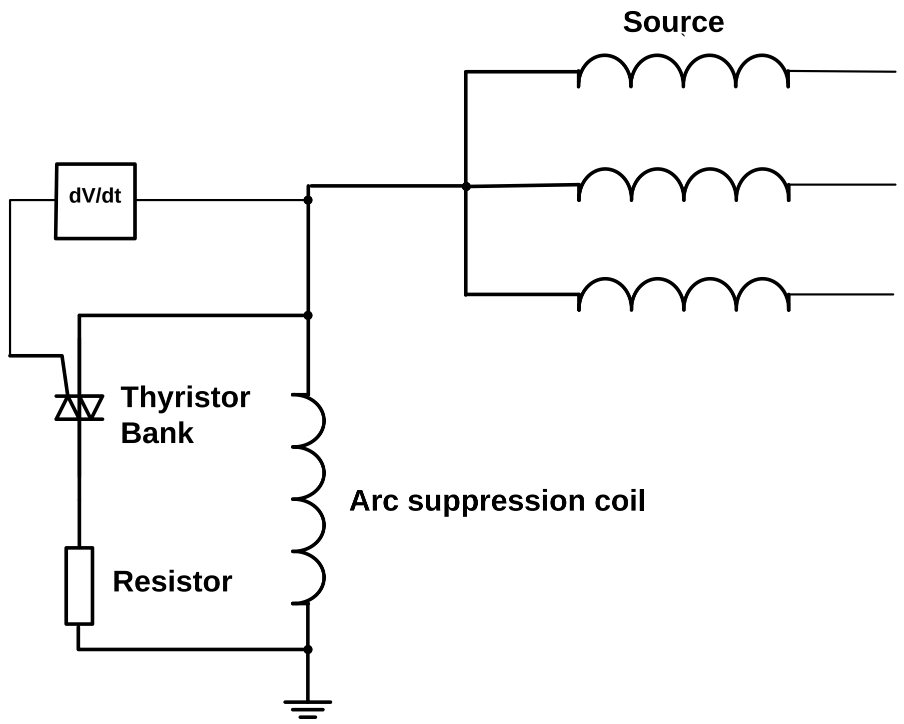


Figure 6.13 Thyristor bank to control transient over-voltages.

The thyristors are triggered by the rate of rise of the neutral voltage. When a single line to earth fault occurs in a non-effectively earthed system, the rate of change of the neutral voltage is very rapid. The derivative of the neutral voltage can then be used to trigger the thyristors very close to the instant of the fault and before the transient oscillations have been established. By then interrupting the current at a current zero, the resultant oscillations are much smaller. In the worst case scenario a half cycle of the 50 Hz normal solidly earthed fault current will flow. A resistor is connected in series with the thyristor bank to limit the maximum current and to reduce the oscillations at the time of the current interruption. One effect of this series resistance is that there are some remaining oscillations in the voltages at the time of the fault. Two thyristor banks of opposite polarity are used to cater for faults occurring at any time in the cycle. The minimum rate of rise of the neutral voltage used to trigger the thyristor banks is selected such that triggering will occur for a single line to earth fault at any location in the distribution system but such that triggering will not occur at the maximum rate of rise of the transient oscillating voltages.

The resulting transient voltages for the previously analysed fault conditions on the urban distribution system are shown in Figure 6.14.

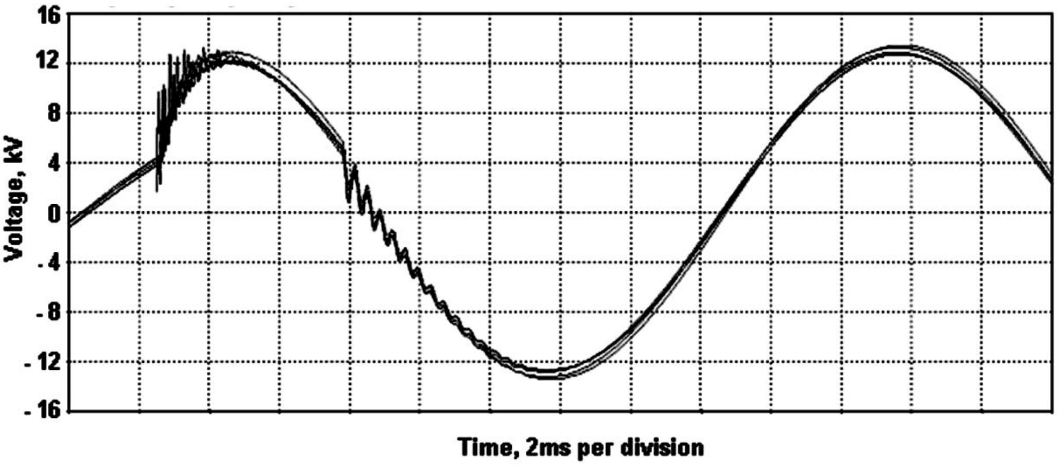


Figure 6.14 Transient voltages on a healthy phase of the urban distribution system with thyristor control.

The resulting transient voltages for the previously analysed fault conditions on the rural distribution system are shown in Figure 6.15.

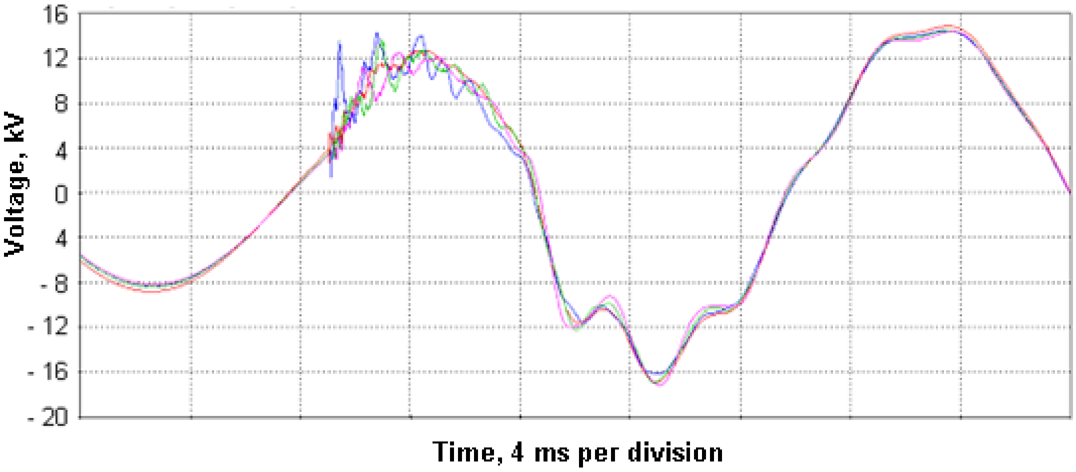


Figure 6.15 Transient voltages on a healthy phase of the rural distribution system with thyristor control.

6.6 Summary

The evaluation methods used confirm that there will be significant over-voltages as a result of transients at the time of the fault in distribution systems using arc suppression coils. Although these transient voltages would not cause cross country faults in a power distribution system that is properly designed and using equipment that is in good condition and which complies with modern standards, there are many distribution systems that have been built many years ago with equipment that has never been tested to the current standards. The equipment may also have deteriorated. A second fault means that there are then two faults that cannot be protected by the arc suppression coil system with possible resultant arcing damage and an increase in the number of permanent faults. A new method to eliminate the over-voltages caused by the transient oscillations is proposed.

It is recommended that network companies considering the installation of arc suppression coil systems in long established solidly earthed systems begin a program of testing existing components to find the capability of the system to withstand these transient over-voltages. In the first instance this can be carried out at low cost by returning for test all otherwise apparently healthy insulating components removed from service for other reasons.

Testing of system components and controlling the magnitude of the transient over-voltages should both be considered as part of the strategy for implementing arc suppression coil systems in power networks that were previously effectively earthed.

Chapter 7 CONCLUSIONS AND FURTHER WORK

Arc suppression coil systems have the potential to improve high voltage power distribution systems in terms of both reliability and safety.

7.1 Analysis of neutral voltages

There is potential for using modern computerised protection systems to determine the type of fault by monitoring the neutral voltage, so that in many cases the appropriate action can be taken automatically. This can provide benefits over and above those of the conventional arc suppression coil installations.

While the relationships between the type of earth fault and resulting neutral voltage has been explored in this dissertation the actual actions taken need to be set out in accordance with policies adopted by the particular electricity network operator. There are good reasons for the various network operators to have different policies. The policies will depend on the most common causes of faults which in turn depend on the design of the network, the incidence and types of weather and human related events. The network operators also need to consider the attitudes of the community to safety and reliability together with the population density of the area in which the power system is situated.

The neutral voltage criteria and appropriate actions need to be incorporated into the further development of intelligent substation and network wide protection systems.

7.2 In-line single phase voltage regulators

A new method of analysing the neutral voltages and currents in systems which include open-delta voltage regulating auto-transformers by the use of symmetrical components has been developed as part of this research. It has been shown in this dissertation that open-delta connected single phase auto-transformers should not be used for in-line voltage regulation in systems fitted with arc suppression coils. Three star connected auto-transformers cannot be used for in-line voltage regulation without impairing the effectiveness of the arc suppression coil system.

In-line voltage regulation can be provided by using three delta connected single phase auto-transformers with the control equipment arranged to keep the three tap change mechanisms in step with each other. The use of distributed static VAR compensation should also be considered as a part of the overall strategy for achieving voltage regulation.

The commonly used single phase auto-transformers connected in open-delta configuration operate independently of each other. Work needs to be carried out in conjunction with the manufacturers to arrange for the control of the three automatic tap changers so that they will remain in step with each other. It would be also advantageous for an out of step alarm to be sent.

The use of three delta connected auto-transformers provides a higher overall voltage boost than that provide by open delta or star connected auto-transformers by a factor of more than 1.5. A common current practice is to provide step voltage increases of 1.25 percent this being the maximum step increase which cannot be easily observed when looking at an incandescent bulb. With the decreasing usage of incandescent lamps, it may be decided that an increase in the step voltage change is acceptable in the rural areas, or it may be decided to arrange for changes in the ratios of the associated auto-transformers be deliberately separated in time by a few seconds. It may also be decided that the increase in the total voltage boost available may be advantageous taking into account the increasing loads in rural areas. If an increase in the total voltage boost is not needed, a redesign of the auto-transformers would produce a smaller core size. Work is needed with the distribution companies and manufacturers to decide whether new standard auto-transformer designs are needed and what sized voltage steps would be appropriate.

7.3 Minimising cross country faults

Provided the insulation capabilities of the existing power systems are properly assessed and the necessary corrective measures taken the incidence of cross country earth faults can be eliminated. In this dissertation simple methods of estimating the likely maximum transient voltages have been provided along with a suggested method of testing to determine whether the existing power system insulation levels are adequate. A new method of reducing the transient voltages is proposed. Any network owner considering the installation of arc suppression coil systems needs to investigate the status of the existing system and allow for the cost of improving the integrity of the existing line to earth insulation of the power system where necessary. Installation of equipment to reduce the maximum magnitude of the transient voltage peaks should also be considered in arriving at an overall plan where the integrity of the existing insulation is found to be deficient.

Detail design of the proposed switched thyristor equipment to reduce the peak transient voltages is needed. This is best carried out in conjunction with equipment manufacturers.

7.4 Cost benefit analyses

This dissertation has looked at some of the technical aspects of arc suppression coil systems. Network owners considering the installation of arc suppression coil systems need to compare the costs with the benefits.

The financial costs can be estimated in conjunction with the commercial suppliers of the equipment together with estimates of the cost of any power system insulation upgrading that is necessary. At present there appears to be only one manufacturer of arc suppression coil systems active in the Australian/New Zealand market. It may be beneficial for network companies in these areas to seek out suppliers of modern arc suppression equipment from elsewhere.

The benefits in power system reliability and safety are less tangible. In order to make a meaningful comparison with the costs they need to be expressed in financial terms.

In economic terms, the cost to the community of a power system interruption can be assessed as the amount members of the community would be prepared to pay to avoid an outage if they had the opportunity to do so. There has been very little research in this area. The issue is further complicated by community cost versus the length of the interruption. The relationship is not linear. For example, at the time when the temperatures inside a domestic refrigerator will no longer be low enough to safely keep food, the cost to the community begins to rise sharply. On the other end of the scale, the cost per minute for the very short duration outages associated with an automatic successful reclose of a feeder is very high.

Some guidance on the costs per minute per consumer of an outage can be obtained in some countries by the financial penalties being imposed on the electricity network owners under the competitive electricity market regime. However in many cases the short term interruptions associated with successful recloses are ignored in these penalty calculations. One of the major advantages of arc suppression coil systems is the elimination of most of these short term interruptions.

The amount the community is prepared to pay to avoid a loss of life or serious injury is even more difficult to assess. A study could be made of the various damages awarded by the courts in accidental personal injury or death cases as a basis for some kind of assessment.

An evaluation of the improvement in reliability to be obtained by installing arc suppression coil systems will involve an extensive analysis of the historical fault events for the particular network. These need to be analysed in terms of the actual causes of the faults so that the alternative scenarios of what would have happened if an arc suppression coil had been installed can be arrived at. In many cases it appears that the existing fault reporting systems do not provide sufficient detail. Short term outages associated with a successful reclosing of a circuit breaker may not be reported at all.

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APPENDIX A1

ANALYSIS OF AN OPEN CIRCUIT COMBINED WITH LINE TO EARTH FAULTS.

A1.1 Unknown quantities and equations

The sequence network for the simple system with an open circuit and simultaneous single line to earth faults at the same location and in the same conductor as shown in Figure 4.18 can be rationalised to that shown in Figure A1.1, where R_{fs}, and R_{fl} are the fault impedances on the source and load sides of the open circuit respectively.

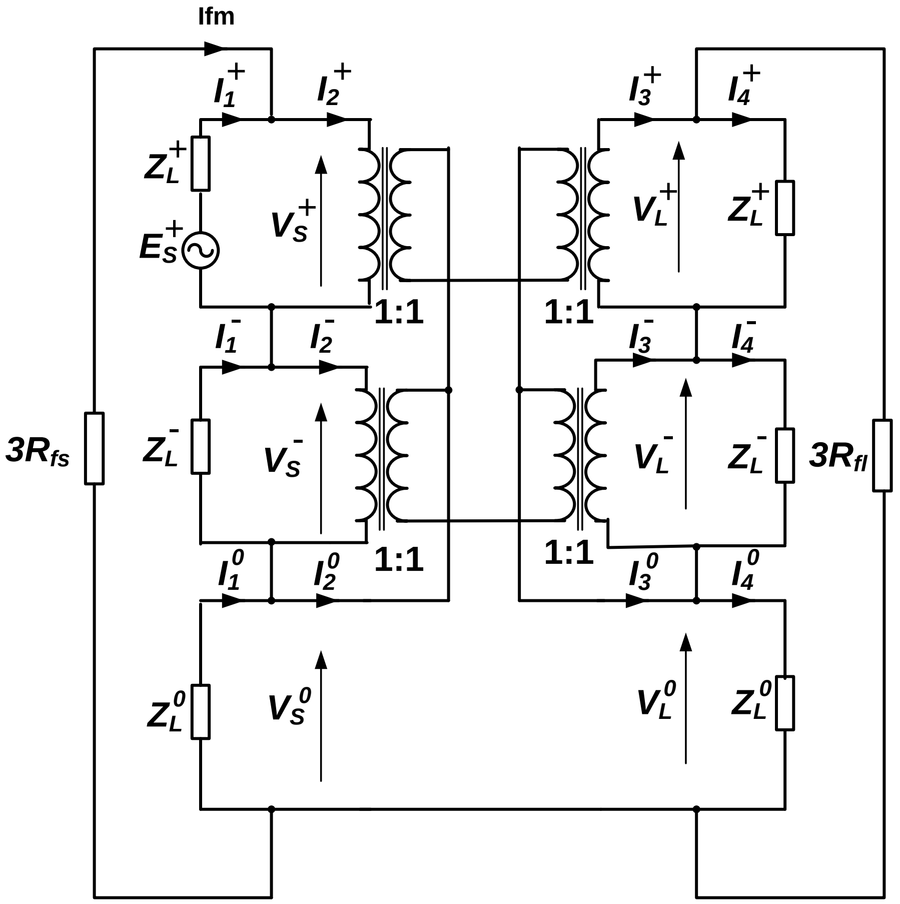

Figure A1.1 Symmetrical component representation of an open circuit with a single line to earth fault on either side of the open point and on the same phase line.

There are 18 unknown quantities as listed in Table A1.1.

Table A1.1 Unknown symmetrical component quantities in a system with a single line to earth fault on either side of the open point and on the same phase line.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
I_1^+	I_1^-	I_1^0	I_2^+	I_2^-	I_2^0	I_3^+	I_3^-	I_3^0	I_4^+	I_4^-	I_4^0	V_S^+	V_S^-	V_S^0	V_L^+	V_L^-	V_L^0

There are 18 simultaneous equations as follows:

$$V_L^+ - Z_L^+ I_4 = 0 \qquad \text{(A1.1)}$$

$$V_L^- - Z_L^- I_4 = 0 \qquad \text{(A1.2)}$$

$$V_L^0 - Z_L^0 = 0 \qquad \text{(A1.3)}$$

$$V_L^+ + I_1^+ Z_L^+ = E_S \qquad \text{(A1.4)}$$

$$V_L^- + I_1^- Z_L^- = 0 \qquad \text{(A1.5)}$$

$$V_L^0 + I_1^0 Z_L^0 = 0 \qquad \text{(A1.6)}$$

$$V_S^+ - I_4^+ Z_L^+ - V_S^- + V_L^- = 0 \qquad \text{(A1.7)}$$

$$V_S^- - I_4^- Z_L^- - V_S^0 + V_L^0 = 0 \qquad \text{(A1.8)}$$

$$I_1^+ - I_2^+ - \frac{V_S^+}{3R_{fS}} - \frac{V_S^-}{3R_{fS}} - \frac{V_S^0}{3R_{fS}} = 0 \qquad \text{(A1.9)}$$

$$I_3^+ - I_4^+ - \frac{V_L^+}{3R_{fL}} - \frac{V_L^-}{3R_{fL}} - \frac{V_L^0}{3R_{fL}} = 0 \qquad \text{(A1.10)}$$

$$I_2^0 + I_2^- + I_2^+ = 0 \qquad \text{(A1.11)}$$

$$I_3^0 + I_3^+ + I_3^- = 0 \qquad \text{(A1.12)}$$

$$I_1^- - I_2^- - \frac{V_S^+}{3R_{fS}} - \frac{V_S^-}{3R_{fS}} - \frac{V_S^0}{3R_{fS}} = 0 \tag{A1.13}$$

$$I_1^0 - I_2^0 - \frac{V_S^+}{3R_{fS}} - \frac{V_S^-}{3R_{fS}} - \frac{V_S^0}{3R_{fS}} = 0 \tag{A1.14}$$

$$I_3^- - I_4^- - \frac{V_L^+}{3R_{fL}} - \frac{V_L^-}{3R_{fL}} - \frac{V_L^0}{3R_{fL}} = 0 \tag{A1.15}$$

$$-I_4^0 + I_3^0 - \frac{V_L^+}{3R_{fL}} - \frac{V_L^-}{3R_{fL}} - \frac{V_L^0}{3R_{fL}} = 0 \tag{A1.16}$$

$$I_2^+ - I_3^+ = 0 \tag{A1.17}$$

$$I_2^- - I_3^- = 0 \tag{A1.18}$$

A1.2 A matlab script to solve the equations

A matlab script to solve these equations and produce the matrix U for the unknown quantities in the order given in the above table is as follows:

Firstly the values for the impedances and the source voltage (E_S) need to be stipulated, then:-

```
M=zeros(18,18);

S=zeros(18,1);

M(16,16)=1; M(16,10)=-ZposL; % Equation A1.1

M(17,17)=1; M(17,11)=-ZnegL; % Equation A1.2

M(18,18)=1; M(18,12)=-ZzeroL; % Equation A1.3

M(13,13)=1; M(13,1)=ZposS; S(13)=Es; % Equation A1.4

M(14,14)=1; M(14,2)=ZnegS; % Equation A1.5

M(15,15)=1; M(15,3)=ZzeroS; % Equation A1.6

M(10,13)=1; M(10,10)=-ZposL; M(10,14)=-1; M(10,17)=1; % Equation A1.7
```

```
M(11,14)=1; M(11,11)=-ZnegL; M(11,15)=-1; M(11,18)=1; % Equation A1.8
M(1,1)=1; M(1,4)=-1; M(1,13)=-1/(3*RfS); M(1,14)=-1/(3*RfS);
M(1,15)=-1/(3*RfS); % Equation A1.9
M(7,7)=1; M(7,10)=-1; M(7,16)=-1/(3*RfL); M(7,17)=-1/(3*RfL);
M(7,18)=-1/(3*RfL); % Equation A1.10
M(6,6)=1; M(6,5)=1; M(6,4)=1; % Equation A1.11
M(9,9)=1; M(9,7)=1; M(9,8)=1; % Equation A1.12
M(2,2)=1; M(2,5)=-1;M(2,13)=-1/(3*RfS); M(2,14)=-1/(3*RfS);
M(2,15)=-1/(3*RfS);  % Equation A1.13
M(3,3)=1; M(3,6)=-1;M(3,13)=-1/(3*RfS); M(3,14)=-1/(3*RfS);
M(3,15)=-1/(3*RfS);  % Equation A1.14
M(8,8)=1; M(8,11)=-1;M(8,16)=-1/(3*RfL); M(8,17)=-1/(3*RfL);
M(8,18)=-1/(3*RfL);  % Equation A1.15
M(12,12)=-1; M(12,9)=1;M(12,16)=-1/(3*RfL); M(12,17)=-1/(3*RfL);
M(12,18)=-1/(3*RfL);  % Equation A1.16
M(4,4)=1; M(4,7)=-1; % Equation A1.17
M(5,5)=1; M(5,8)=-1; % Equation A1.18
U=M^-1*S;
```

APPENDIX A2

ZERO SEQUENCE CAPACITANCE OF TRANSFORMERS CONNECTED TO THE LINE

Tests were carried out to evaluate the likely influence of the zero sequence capacitance of distribution transformers connected along the line. A typical 200 kVA, 11 kV/415 V, Dy11, outdoor type transformer was tested with the terminals connected as shown in Figure A2.1.

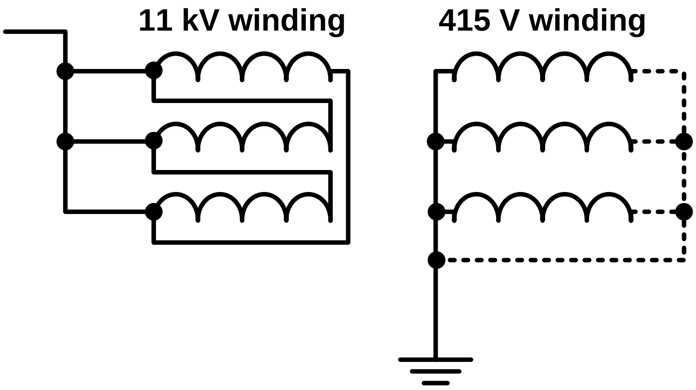

Figure A2.1 Connections for testing the zero sequence capacitance of a typical transformer

To accurately simulate the conditions in service the actual load should be connected to the 415 volt terminals. However, because of the relative impedances, it was found in the following tests that the same readings were obtained with and without the low voltage terminals shorted to earth.

The capacitance between the high voltage winding, and the earthed low voltage winding was measured with a capacitance meter. The value was found to be 0.0089 μF. As this is the total capacitance of all three phases it follows that the zero sequence capacitance is:

$$C_0 = \frac{0.0089}{3} = 0.00297\,\mu\text{F}.$$

A test voltage of 11kV at 50 Hz was then applied the high voltage winding and the earthed low voltage winding. The current flow was found to be 32 mA.

Using these figures and ignoring any losses the zero sequence capacitances is calculated as:

$$C_0 = 0.0031\ \mu\text{F}.$$

Although the difference in impedance may have been due to winding inductance, the result is within the accuracy limits of the measurements taken.

A typical 11 kV overhead line has a zero sequence capacitance of about 0.00425 µF per km. This transformer zero sequence capacitance equates to about 700 metres of line. For smaller transformers the zero sequence capacitance will be a lower value.

A sample of typical 11 kV/415 V, 3 phase transformers were connected as shown in Figure A2.1 and tested with a capacitance meter. The results are shown in Table A2.1.

Table A2.1 Capacitance of HV winding to LV winding and earth for a sample of typical 11 kV to 415 V transformers.

Size (kVA)	**Make**	**Capacitance (nF)**
25	PLC	2.02
63	ABB	4.14
100	Wilson	4.63
200	ABB	9.62
200	ABB	9.84
200	Wilson	7.58
500	ASET	5.45