

A GUIDE TO EARTH RETURN CURRENT CALCULATION **PART 1: FUNDAMENTALS AND ANALYSIS**

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PURPOSE AND SCOPE

This Guidance Note describes the importance of the Rise of Earth Potential study. It also outlines the essential factors that have to be considered in such studies. It describes in detail the technical background in the standard industry approach.

PART 1 –PROCEDURAL

1 INTRODUCTION

During an unbalanced fault within a National Grid substation, large currents can flow through the substations' earthing system. The impedance of the earthing system, although small, may cause a considerable rise in potential of the earthing system and any metallic structures within the site that are bonded to it. There is an obvious need to evaluate the maximum possible rise of potential in order that the substation may be operated safely.

The impedance of a substation earthing system may be obtained from direct measurement or through calculation alone. To evaluate the maximum possible rise of earth potential, all that remains is to determine the largest possible current that can flow through the earthing system. This will usually arise for a fault within the substation, but may under certain arrangements arise for an overhead line fault just outside the substation.

Fault current supplied via an overhead line or from a cable circuit does not return to the source supplying it through the soil alone. A certain percentage of the current will flow

through the earth wire or cable sheath. This current does not enter the ground and therefore does not contribute to rise of potential (RoEP) at the site.

The Earth Return Current I_{gr} , is defined as the current flowing through the earthing system impedance, which in turn gives rise to the substations RoEP. The Earth Return Current may be obtained by determining the current distribution between that returning through the soil and that returning through metallic paths.

This guidance note describes a simplified method based on Engineering Recommendation S34 [1] for the evaluation of earth return current at a National Grid substation. The calculated value of earth return current may then be used for subsequent RoEP calculations. The guidance note has been divided into different sections, Section 3 provides a technical background to the evaluation of earth return current. More technical background for the calculation of earth return current and a numerical example will be given in appendices.

2 ESSENTIALS FOR AN EARTH RETURN CURRENT CALCULATION

- a) In a substation, all exposed metallic parts are bonded to the substation earth mat.
- b) The substation earthing impedance is usually very small, typically in the range 0.01-0.6 Ω . However during an earth fault at a substation, because the fault current is very high at the point of fault the substation earth mat potential rises with respect to general mass of earth or the zero Volt plane.
- c) Limits are provided in standards for the rise of the earth mat potential in the form of touch and step voltages and other criteria.
- d) During a fault involving earth, not the entire fault current returns to the source supplying the current through earth.
- e) In order to avoid over-estimation and hence extra cost, the components of the fault current that do not enter earth at the fault point are separated from the fault current.
- f) The earth return current is based on the zero sequence component of the fault current. Only 400kV, 275kV and 132kV PE (Phase-Earth) and PPE (Phase-Phase-Earth) faults occurring within the substation are considered in this document.
- g) Part of the fault current returns to the source supplying it via the overhead line earth wire or cable sheath.
- h) The currents returning to source via earth wire or cable sheath have two main components, due to magnetic induction between phase conductors and earth wire or cable sheath and as a result of conduction due to earth wire or cable sheath self impedances and terminating or earthing resistances.
- i) The basis of the earth return current calculation adopted here is to separate the inductive components first.
- j) For overhead lines, the proportion of the fault current that returns via the earth wire is mostly proportional to the self impedance of the earth wire and mutual impedance between the earth wire and the phase conductor.
- k) The concept of a screening factor, 'k', has been introduced by Engineering Recommendation S34 for some typical overhead line constructions. This is an approximate method to separate the portion of the fault current that enters earth from the total fault current. Screening factors used for National Grid and DNO circuits are those detailed in ER S34 and will be shown in this guidance note for ease of reference. The screening factors are proportional to the inductive components of the earth wire current.

- l) Screening factors for overhead lines given in ER S34 are valid for line lengths of longer than 20 span.
- m) The screening factor for wooden poles with no earth wire is $1 \angle 180^\circ$, thus the entire fault current enters earth.
- n) For lines shorter than 20 spans, assessment should be done to check the actual screening factor for the line and the influence of the terminating and earthing resistances on the earth return current.
- o) For long cable circuits with complex cross bonding, single and multiple earthing bonding, detailed modelling is required to determine the earth return current.
- p) ER S34 provides nomograms for cable circuits. These nomograms apply only to simple, short and specific configurations. The nomograms do not apply to XLPE cables if the cable self and mutual impedances are very different to those cable types considered to determine the nomograms. Appendix C describes methods for using nomograms.
- q) If there is additional earth wire in parallel with the cable circuit then the nomograms are not valid and should not be used. Detailed modelling is required.
- r) Sometimes, a short cable is used at the substation entry. Because the cable is short, the cable sheath may be solidly connected to the substation earth mat at one point and connected to the same earth mat via sheath voltage limiters at the other end which means that no circulating current can flow. The overhead line earth wire is connected to the substation earth mat at the line and cable junction. In this case, the screening factors in S34 for overhead lines can be used provided all requirements in using k factor are met.
- s) The substation earth mat may be tied into other earth mats belonging to DNO and/or power station companies. It is assumed that this interconnection is sufficient to allow the separate electrode systems to be treated as a combined earthing system.
- t) If two substations' earth mats are connected by short cables and/or overhead lines the screening factors in ER S34 do not apply. The actual cable/line screening factor should be determined first and the earthing impedance of both substations should be considered.
- u) Although power stations increase the fault current, they have to be treated as out of service for the earth return current calculations. This is because the delta winding of the generator transformer reduces the earth return current and thus does not give the worst case scenario for the site under consideration. Generation connected to the site being studied (on the same earth mat) is removed from the study i.e. fault current can only come from the external system.
- v) Two and three winding transformers with a delta winding reduce the earth return current because part of the fault zero sequence current circulates within the path provided by the transformer delta winding without entering earth. This component of the fault current should be subtracted from the total fault current.
- w) A winter-peak model is used as this gives rise to the highest fault levels on the system.
- x) The substation running arrangements are modified to provide the worst-case scenario. Split busbars at the substation under consideration and adjacent external substations should be operated solid if this is a credible operating arrangement. The modifications should not be overly pessimistic, but should reflect credible situations.

- y) Given the uncertainty over the construction of DNO feeder circuits, all DNO infeeds will be treated as L4 overhead line circuits (except in the case of wood pole lines). This will give the highest earth return current ratio and is pessimistic. Note that DNO wood pole 132kV overhead lines do not have an earth-wire. In this case the screening factor will be $1.0 \angle 180^\circ$ pu.
- z) The sub-transient RMS current is used for the calculations.
- aa) Given the uncertainty that the fault level will remain at or below the studied level for the period for which the earth return current calculation is valid (six years in the case of routine assessment calculations), a margin of +10% is added to the calculated value of earth return current. This is in accordance with NGTS 3.01.02 which allows up to +20% for uncertainty. It is justified to use this lower margin due to more accurate network data and modelling.

3 FUNDAMENTALS OF EARTH RETURN CURRENT CALCULATION

The National Grid transmission system is a multiple-earthed system; all supergrid transformer neutrals are bonded to earth. The vast majority of supergrid transformer neutrals are solidly bonded to earth such that there is no deliberately introduced impedance between the neutral point and the general body of the earth. However, a small number of supergrid transformers (eg Creyke Beck substation) do have small deliberately introduced reactances between their neutral point and earth in order to limit earth fault currents.

Although a large magnitude fault current during unbalanced earth faults is advantageous in terms of being easily detected, it does result in a large current flowing from the substation earth mat into the general body of earth (hereafter referred to as *remote earth*). The impedance between the substation earth mat and remote earth is generally small, but because the current flowing into earth is large there will be a significant rise in potential of the earth mat, and any metallic structures within the substation that are bonded to it, relative to remote earth. In order to safely manage this situation, it is necessary to evaluate the maximum possible rise of potential of the substation earthing system.

3.1 Earthing System Components

A substation earthing system can be divided into two distinct components, a main earth grid or main earth system (MES), and an extended electrode system.

Main Earth Grid: The earth mat forms the main connection to the general body of earth within a substation. It consists of a horizontal copper tape mesh buried at 0.6 metres below ground, connected to which are vertical driven copper rods (1m to 15m in length) at key locations around the site. All of the exposed metalwork in the site (e.g. bus-bar support structures, circuit breaker frames, transformer neutral points etc) is bonded via copper earth tape to the earth mat. As shown in Fig 1, where there is an adjacent site such as a distribution network operator (DNO) substation or power station, the National Grid earth mat will be bonded to these additional earth mats via dedicated earth-bonds. Also note that terminal towers are bonded to the substation earth mat by buried earth-bonds.

The earth impedance of the grid is mainly resistive and is largely inversely proportional to the surface area it covers and the resistivity of the soil in which it is located.

Extended Electrode System: The earth wires and cable sheaths associated with the feeders connected to the substation act as additional earth electrodes. The effective area of the earthing system is increased, helping to secure low overall earth impedance.

The earth impedance of an extended electrode system (overhead line earth wire and cable sheaths) will contain a significant reactive component.

Overall Earth Impedance: The overall substation earthing impedance can be approximated by considering the parallel combination of the earth grid resistance and the impedance of any extended electrodes. This will generally lie in the range of 0.01Ω to 0.6Ω .

The terminal tower structure and earth-wire termination of each overhead line route is solidly bonded to the substation earth mat. This results in the size of the substation earthing system being increased considerably because the earth-wire is solidly bonded to each tower along the route.

The earthing arrangement of a cable circuit depends upon the operating voltage and the length of the cable. In general, the cable sheath will act in a similar fashion to an overhead line earth-wire to increase the effective area of a substation earthing system.

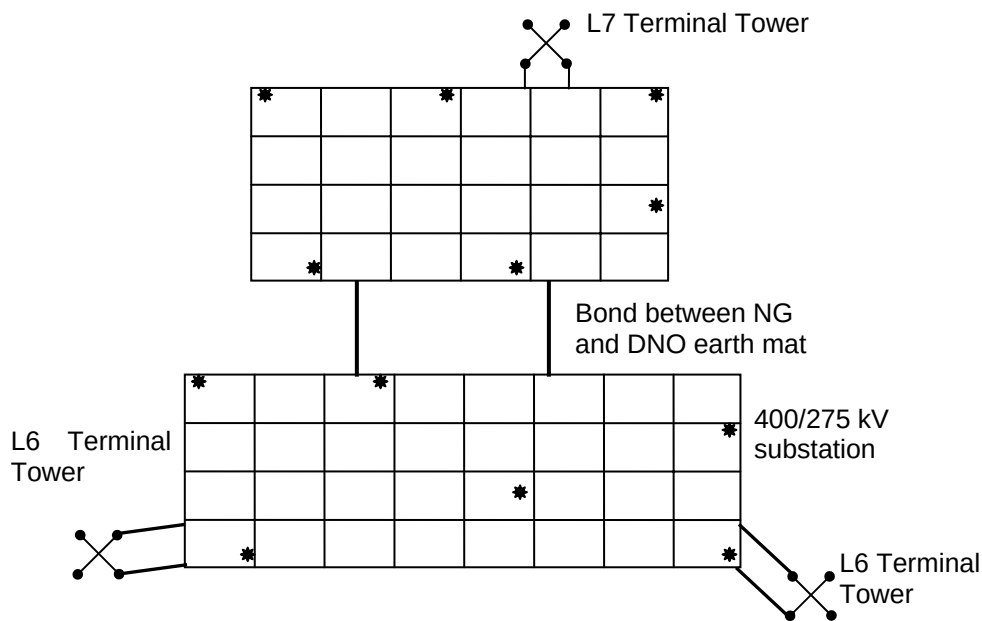


Fig 1- Plan View of a Substation Earth Mat

3.2 Rise of Earth Potential and Earthing System Impedance

3.2.1 Normal operation

During normal operation of the power system, the earthing system will be at a potential very close to that of remote earth. Under normal conditions zero phase sequence (ZPS) currents in overhead lines are, by design, kept as low as possible so the ZPS current returning to source via substation earthing systems is low, hence the residual voltage on the earthing system is of the order of 10V-20V with respect to remote earth.

3.2.2 Fault conditions

During a balanced three-phase to earth fault (PPPE) within a substation no net fault current enters the earthing system so there is no increased rise in potential of the earthing system with respect to remote earth.

During an unbalanced earth fault within a substation such as a single phase to earth (PE) or two phase to earth (PPE) fault, a large current will flow through the earthing system returning to the sources remote from the site. One of the key functions of an earthing system is to provide a low impedance path for fault current to flow to earth, but in reality, although the impedance is small, the large magnitude of the fault current can result in a potential rise in excess of a few hundred volts, or even as high as a few kilovolts.

3.2.3 Equivalent impedance of the earthing system

To understand the nature of the impedance between the substation earthing system and remote earth, it is useful to examine the properties of each component in turn.

The earth mat impedance is predominantly resistive and is usually referred to as the earth mat resistance (R_g). The earth mat resistance is proportional to the soil resistivity and inversely proportional to the surface area covered by the earth mat. Vertically driven rods are useful in situations where low resistivity soil is found below a high-resistivity surface layer. It would be impractical to install the earth grid at a depth greater than 2 metres below the soil surface. The resistance of the metalwork forming the earth grid is generally negligible compared to the resistance of the volume of soil in which the electrode system is buried. Fig 2 illustrates a substation earth mat and its electrical representation.

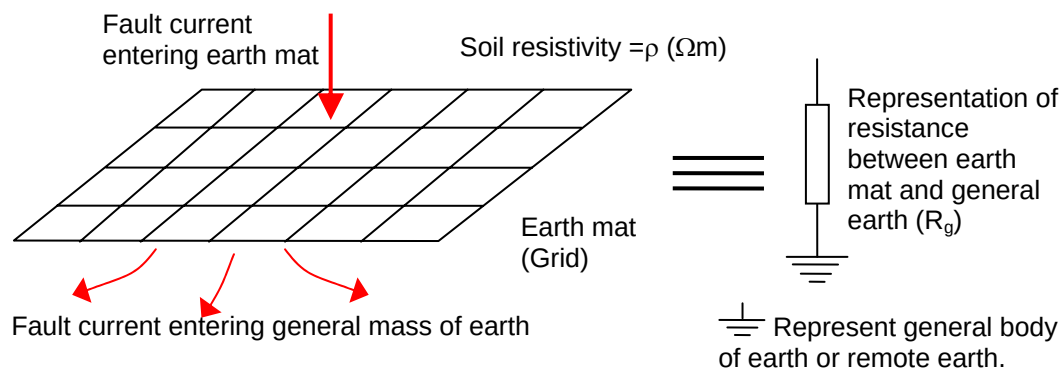


Fig 2- Earth Resistance (R_g) of a Substation Earth Mat

The current in the earth wire has two main components, due to induction effect and through conduction. Both will be described in detail later in this guide. The parameters that affect these currents are the mutual impedance between earth wire and the main phase conductors, the self impedance of the earth wire and the impedance of the tower to the general body of the earth. The earth wire is connected to the tower at each tower location which is in turn earthed.

The impedance of an overhead line earth-wire connection is again dependent upon soil resistivity, and contains an appreciable reactive component. It is usual practice to consider the overhead line as a chain-impedance; this can be reduced to a single shunt element (Z_{ch}) relative to remote earth. The two parameters of interest are the earth-wire self impedance (Z_{es}) and the tower footing resistance (R_t). It is usually assumed that the span length is constant (typically 300 metres) and that the footing resistance of each tower is identical along the whole route.

The tower footing resistance will be largely inversely proportional to the size of the tower (i.e. an L6 tower will have a lower footing resistance than an L8 tower in the same soil resistivity). The earth-wire impedance depends upon the physical size of the earth-wire, tower construction, the span length and the soil resistivity. Each overhead line will have associated chain impedance. Fig 3 illustrates the chain impedance of the earth wire and tower footing resistance.

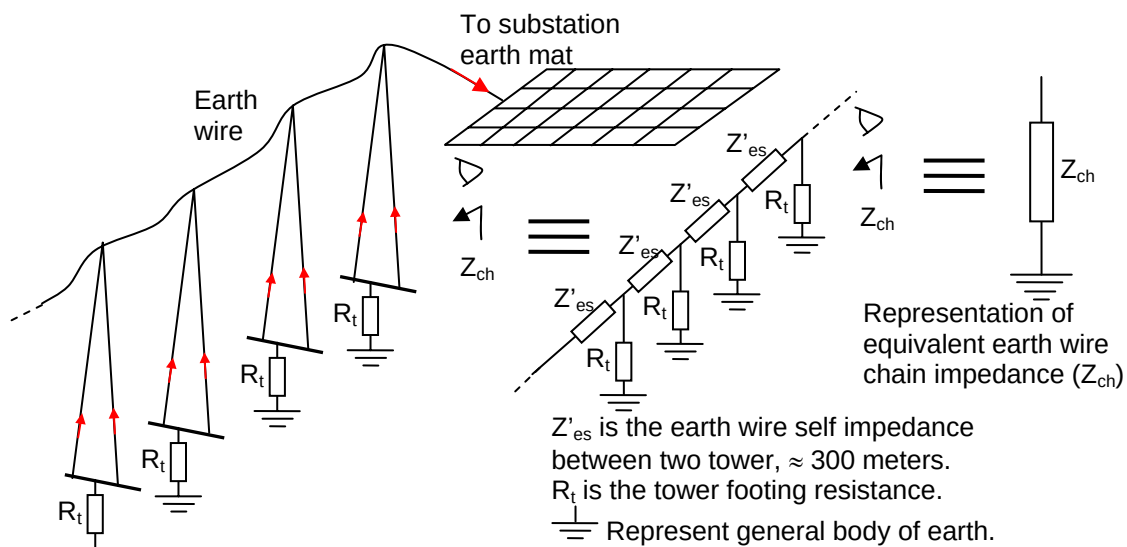


Fig 3- Chain Impedance of Earth Wire

A similar approach can be applied to cable circuits, but this requires the bonding and earthing arrangements to be specified, and the mutual interaction between parallel cable sheaths to be taken into account. Analysis of cable circuits is more time consuming as the full cable installation including the junction boxes should be modelled. Cross bonding is used to minimise the voltage in sheath. The sheath is not earthed at all junction points to reduce the current but only at major bonding points. In order to limit the sheath voltage during a fault condition sheath voltage limiters (non-linear resistors) are used at junction points where the sheath is not earthed. These points are called minor junction points. The combination of these arrangements affects the equivalent cable impedances. Fig 4 illustrates a typical cable installation. Regardless of the approach, an equivalent earthing impedance Z_{cable} can be derived.

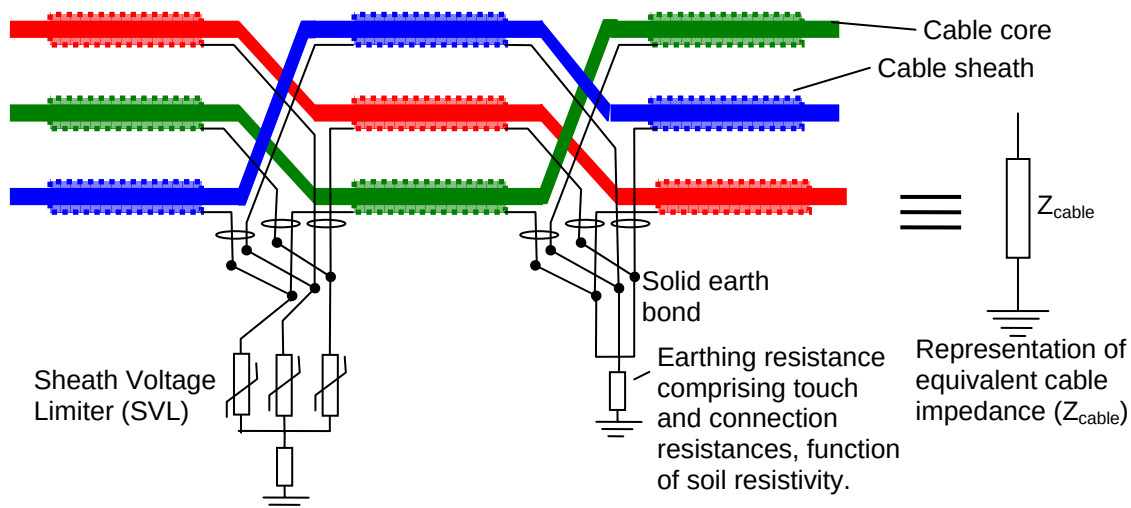


Fig 4- Typical Cable installation with Minor and Major Junction Point

3.2.4 Overall Earthing Impedance

The overall earthing system impedance can be approximately estimated by considering the parallel combination of each of the components forming the earthing system. The overall

earthing system impedance is the impedance to remote earth seen at the point of fault. The impedance of a substation overall earthing system may be obtained from direct measurement or by calculation. In practice, this impedance is found to range between 0.01 ohm and 0.6 ohm. Fig 5 shows the equivalent overall impedance between the fault point and the remote (general) earth.

The rise of earth potential (RoEP) is the product of the overall earthing system impedance (Z_{gre}), and the current flowing through this to remote earth. This current, known as the *earth return current* (I_{gr}), is not the same as the fault current. There is an important difference which will be explained later in this guide.

The equivalent impedance seen by I_{gr} is given by:

$$Z_{gre} = \left(\frac{1}{R_g} + \frac{1}{Z_{ch}} + \frac{1}{Z_{cable}} \right)^{-1} \quad (1)$$

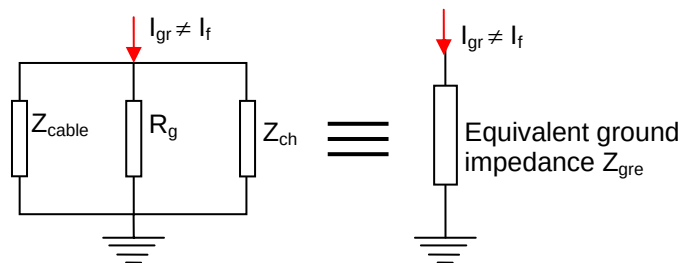


Fig 5- Equivalent Overall earthing System Impedance Z_{gre}

3.3 Current Components at the Fault Point

As has been mentioned, the overhead line earth wires and/or cable sheaths are bonded to the substation earth mat like any exposed metallic part of other equipment. Thus, fault current supplied by the phase conductor of an overhead line with an earth wire or cable circuit does not return to the source supplying it through earth alone. A certain proportion of the fault current will flow back to source via the overhead line earth wire or cable sheath entering the line earth wire or cable sheath through the substation earth mat without entering the ground. As this component of current does not flow into the substation ground impedance it does not contribute to the earth return current and hence to RoEP of the substation earthing system. Fig 6 illustrates the current flow during an earth fault at a substation.

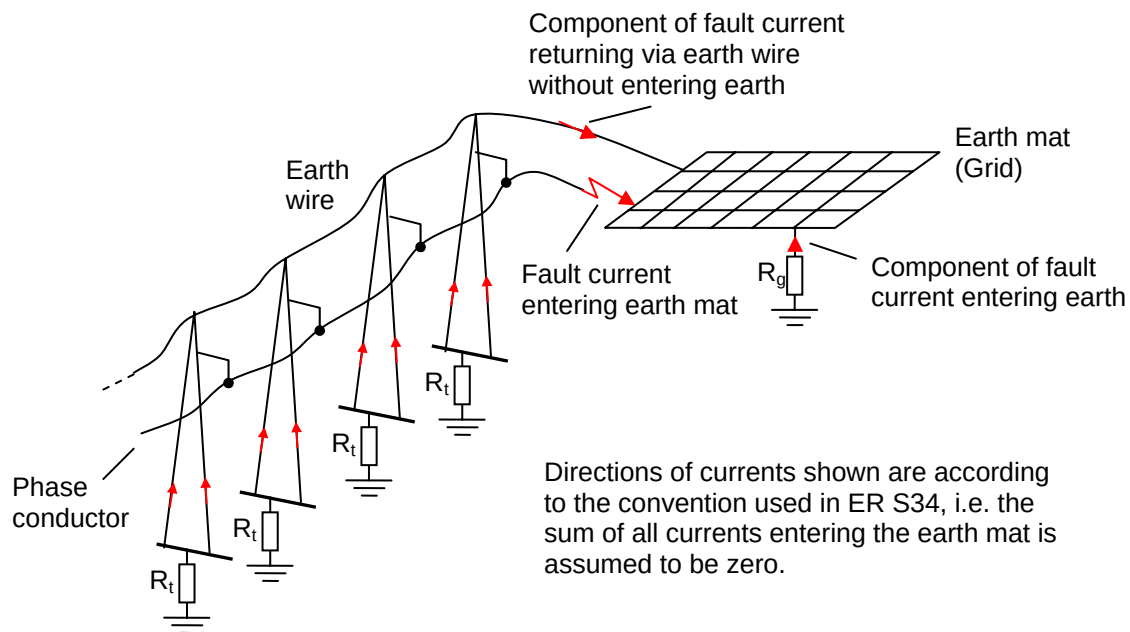


Fig 6- Schematic of Fault Current Components for a Substation Earth Fault

The earth return current is derived from zero phase sequence (ZPS) short-circuit currents entering an earth fault at a substation from short-circuit current sources external to the substation. It is, therefore, only necessary to take account of ZPS short-circuit currents from circuits entering the substation for purposes of earth return current calculation. **Error! Reference source not found.** shows the relationship between the PE and PPE fault currents and their ZPS components. Therefore all earth return current and RoEP analysis are carried out with respect to the zero sequence current of the fault current.

3.3.1 Current Returning Through Overhead Line Earth Wire

When a conductor lies parallel to another in which alternating current flows, a longitudinal emf will be induced in it. If the conductor is earthed at both ends of the parallelism then the current will circulate through it, flowing sensibly in opposite direction to the inducing current (Lenz's law). Overhead line earth wires and cable sheaths/armours are such conductors in which quite large induced currents can flow when associated circuit phase conductors carry earth fault current. That proportion of the current induced into the earth wire or cable sheath/armour does not contribute to the rise of earth potential.

The ZPS current flowing in the earth-wire under fault conditions has two components; one component is due to conduction and the other due to inductive coupling with the main phase conductors.

The inductive component is related to the self impedance of the earth wire and also mutual coupling between the earth wire and the phase conductors. The conductive part depends on the self impedance of the earth wire and the equivalent earth impedance Z_{ge} .

In the case of an overhead line, the conductive component of fault current returning along the earth-wire will dissipate into earth through the footings of towers in the vicinity of the fault point. As the distance from the fault point increases this component will decrement to a negligible value. For a typical overhead line, it is likely that the conductive component of ZPS current returning through the earth wire will have reduced to a negligible value after 20 spans effectively leaving just the inductive component of ZPS current flowing in the earth wire. This dissipation very much depends on the towers footing resistances. In the case of a