The following factors need to be considered:

(a) *Personal safety*

The fault clearance time of the first upstream primary protection device, e.g. primary protection time plus circuit breaker break time, total fault clearing time of a fuse) shall be used for personal safety against a worst case fault magnitude. Where High Speed Single Phase Auto Reclosing (HSSPAR) is used the clearing times for the two events (or multiple events) should be summated. HSSPAR is used on transmission lines, not on distribution lines (which typically have much longer no-voltage times between successive auto reclose attempts).

The assessment of step and touch voltage hazards often requires the consideration of a number of earth fault scenarios with different fault clearing times (other than primary). It is then necessary to evaluate which combination of fault current and clearing time represents the worst case for step and touch voltage hazards assessment. Quite often, it may be necessary to assess more than one set of fault current and fault duration scenarios.

(b) *Conductor sizing*

Fault duration (corresponding to total clearing time), also determines the electrical rating of earthing conductors. The conductor and connecting joint thermal requirements should be of sufficient size to withstand maximum earth fault current for back-up protection operating time plus circuit breaker operating time.

8.4.4.4 *Soil resistivity*

As soil resistivity and soil structure have significant effect on earth potential rise of the earthing system, care must be taken to ensure that reliable data is obtained from field testing encompassing a sufficiently wide traverse in order to establish resistivity variations with depth. Consideration shall be given to the variation of soil resistivity due to temperature and moisture.

8.4.4.5 *Layout practicalities*

Where influence on property selection for a substation site is possible, data gathering in all categories listed in Clause 8.4.3 will help determine the site which best achieves a simple and effective earthing system design. Possible transferred voltage hazards may dominate site selection.

Influences which may prevent the best layout and positioning in terms of an earthing system include minimizing earthworks and the protection of vegetation, and although in the end, such influences may override gains achieved in the efficiency of the earthing system, it is important that all aspects be considered in the final decision.

8.4.4.6 *Coordinated design*

Earthing system design should take into consideration interactions with the following systems (if applicable):

(a) Metallic pipelines.

(b) Telecommunications network.

(c) Metallic structures (e.g. fences, hand rails, conveyors, industrial plant).

(d) Interconnected power earthing systems.

NOTE: The use of interconnected earthing system is recommended unless separation provides a lower overall risk.

8.4.4.7 *Current injection*

Current injection testing may be employed during the initial design phase in order to gather information about the behaviour of existing earthing systems. This can provide a fall of potential (surface gradient) of the soil and input impedance of an existing earthing system.

8.4.4.8 *Special considerations*

Special considerations may be necessary which include the following:

(a) *Staged implementation*

The design must also consider any known staging requirements during the course of a project, identifying and designing out any associated touch, step and transferred potential conditions at the timing of each stage.

(b) *Gas insulated switchgear (GIS)/gas insulated line (GIL)*

The earthing system of GIS and/or GIL may need special consideration due to—

(i) reduced substation area;

(ii) induced currents; and

(iii) high frequency transients.

8.4.5 Determine design EPR

Based upon the soil characteristics and the likely proportion of total earth fault currents flowing into the local earthing system the expected EPR is calculated for each of the key fault cases identified. This is the major outcome of the initial design concept phase as it enables assessment of which areas require further consideration. Fault scenarios that are not significant may be acknowledged and discounted from further analysis.

This first pass sets a conservative upper limit for the EPR. It enables assessment of which fault scenarios should be the focus of the detailed design effort. Some fault scenarios may later be shown to exhibit a maximum EPR that is less than the applicable compliance criteria (e.g. relevant V/t design criteria) and so achieve compliance without specific mitigation. These values are critical in that all other hazard voltages (e.g. step, touch, transfer) are calculated by scaling based on the relative EPRs for each key fault case.

8.4.6 Power frequency design

8.4.6.1 *General*

The power frequency design of an earthing system should take into account all the relevant parameters. The design parameters critical to the design include the fault current magnitude, fault current duration, soil resistivity, current splits, earth grid area, interference and coordination. A number of the design parameters are briefly discussed in the following clauses.

8.4.6.2 *Earthing conductor layout*

An earthing system bonds the required equipment and structures to the general mass of earth via some form of earth grid. The physical practicalities of the design need to achieve a level of robustness for the life of the installation. Earthing equipment and material selection is therefore critical. The method of installation and manner in which conductors are protected, the level of redundancy and the corrosion consideration employed will need to ensure the correct outcomes are achieved. The design should specify conductor sizing, terminations, acceptable jointing methods, material types, conductor protection, provision for portable earthing, labelling and inspection and testing requirements as a minimum. Special consideration should be made to ensure the integrity of connection between critical equipment and the earthing system. Many of the provisions are addressed in some detail in other guides such as ENA EG-1 and IEEE Std 80 [1].

8.4.6.3 *Dimensioning of earthing conductors*

Parameters relevant to earthing system dimensioning include magnitude and duration of fault current and soil characteristics. These parameters combine to define conductor sizing in terms of electrical and mechanical rating:

(i) *Electrical rating*

For electrical rating, the fault currents used to calculate the conductor size should take into account the possibility of future growth. The temperature rise involved in calculating electrical rating shall be chosen to avoid reduction of the mechanical strength of the earthing system (including conductor jointing) and to avoid damage to any surrounding materials, (e.g. concrete or insulating materials).

Back-up relay protection operating time, plus circuit breaker break time should be used when designing conductor and connecting joint thermal requirements. For conductor sizing the total accumulated fault time needs to be considered where auto-reclose is applied, as there is very little cooling during the auto-reclose dead time.

Consideration may also be given to current splitting on the assumption that fault current on entering the buried section of the earth grid travels in multiple directions, and, as such, these buried conductors are not required to be rated at full fault current.

(ii) *Mechanical rating*

Externally applied forces (resulting in physical stress of the conductor) include direct impact, soil movement and compaction of surrounding soil.

Electromagnetic forces are due to the flow of fault current through the conductor and although significant, do not dictate minimum conductor size. However, where a conductor is used for down leads from mounted equipment to earth grid connection points, they shall be fastened to the structure as often as necessary to withstand the short circuit dynamic forces.

The earthing conductors, being directly in contact with the soil, shall be of materials capable of withstanding corrosion (chemical or biological attack, oxidation, formation of an electrolytic couple, electrolysis, etc.). They have to resist the mechanical influences during their installation as well as those occurring during normal service. Note that composite conductors can also be used for earthing provided that their electrical and mechanical properties are equivalent and do not compromise the integrity of the earthing system. Aluminium conductors shall not be used for buried earthing applications.

It is acceptable to use steel reinforcing bars embedded in concrete foundations and steel piles as a part of the earthing system, provided thermal ratings for conductors and joints are not exceeded.

To prevent theft and/or vandalism, consideration should be given to protecting exposed components and/or selecting alternative materials.

For direct buried or exposed conductors a minimum size of 35 mm^2 copper equivalent conductor is considered prudent for high voltage earthing. Further guidance regarding sizing of conductors to meet thermal requirements is given in the ENA EG-1.

Provision for portable earthing should meet electrical and mechanical rating requirements, be located for convenient and safe usage (including putting on, taking off), and facilitate maintenance.

8.4.6.4 *Transferred potentials*

Earthing systems can cause inductive and conductive interference to other metallic systems which requires coordination. Consideration shall be given to the following:

(a) *Transferred potentials to plant, personnel and the public* The substation earthing system shall be designed to ensure that interference with other utilities, plant and personnel (e.g. telecommunications, pipelines, railways, mine infrastructure, houses, LV MEN), by conductive or inductive coupling, takes into consideration appropriate standards and guidelines.)

(b) *Corrosion control* Earthing system components may be subject to corrosion from, or be the cause of corrosion in, other systems. Corrosion control coordination may also extend to the interconnection of different earthing systems comprising of different earthing materials (e.g. power station and adjacent transmission switchyard).

8.4.6.5 *Hazard location identification*

The design shall identify locations where personnel or the public may be exposed to shock hazards. Such hazards include, touch, step, transfer and hand-to-hand contacts shown in Figure 8.2. Hazardous step and touch voltages can appear on the metal structures or equipment associated with high voltage power systems, or may be transferred via soil, metal structures or equipment located near high voltage power systems due to one or a combination of the following factors:

(a) Electrical insulation failure or mechanical failure or both.

(b) Human error, resulting in accidental livening of station equipment, and/or lines circuits.

(c) Electric field (capacitive) coupling.

(d) Magnetic field (inductive) coupling.

Hazardous voltages on conductive parts may appear between the hand and one or both feet of a person, or between the two hands (i.e. reach touch voltages). Hazardous voltages may also appear across the surface of the ground and therefore between the feet of a person (i.e. step voltages). Such voltage differences can occur within and around HV installations, and also on metallic structures along the length of, or close to power lines, under earth fault current conditions.

Voltage differences may also need to be controlled, to ensure that insulation breakdown or failure does not occur on apparatus connected to points outside the station. Cable sheaths, metallic pipes, fences, etc. which are connected to the station earthing system will transfer earth fault voltages from the station earth electrode to the remote points. Similarly, cable sheaths, metallic pipes, etc. which are connected to remotely earthed structures but isolated from the station earth electrode will transfer the earth fault voltage of the remote structure into the station.

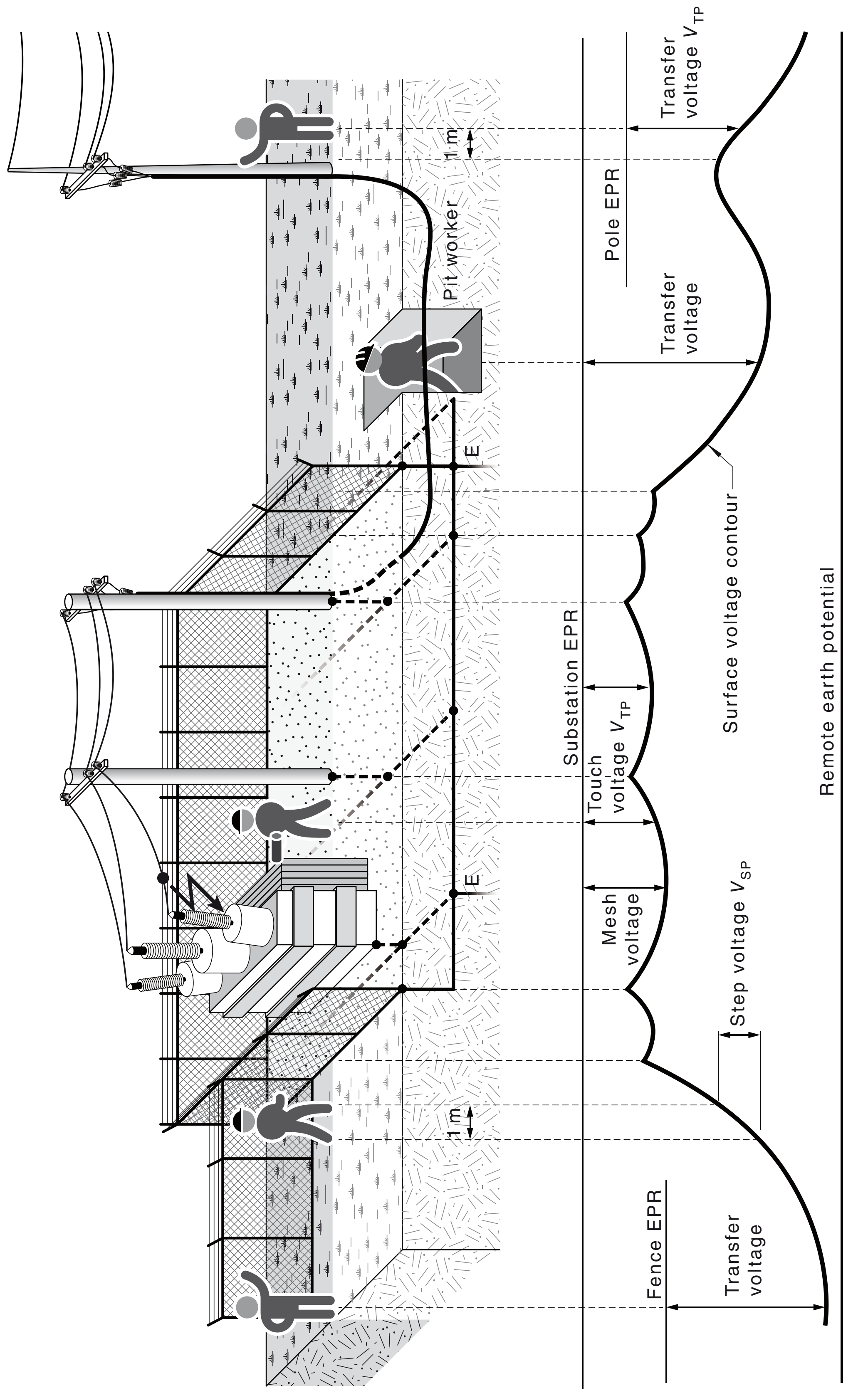


FIGURE 8.2 HAZARDOUS LOCATIONS RELATED TO AN EARTH FAULT (EPR)

The specific hazard locations will represent different risk profiles by virtue of the fact that there will be different coincidence probabilities of system events and human contacts and different series impedance (for example, footwear and surface coverings). Consideration should be given to factors such as the following:

(i) Probability of multiple simultaneous human contacts (particularly in public places), (i.e. touch, step, hand-to-hand or transfer voltage impacts).

(ii) Susceptible locations (wet areas with little or no additional series resistance).

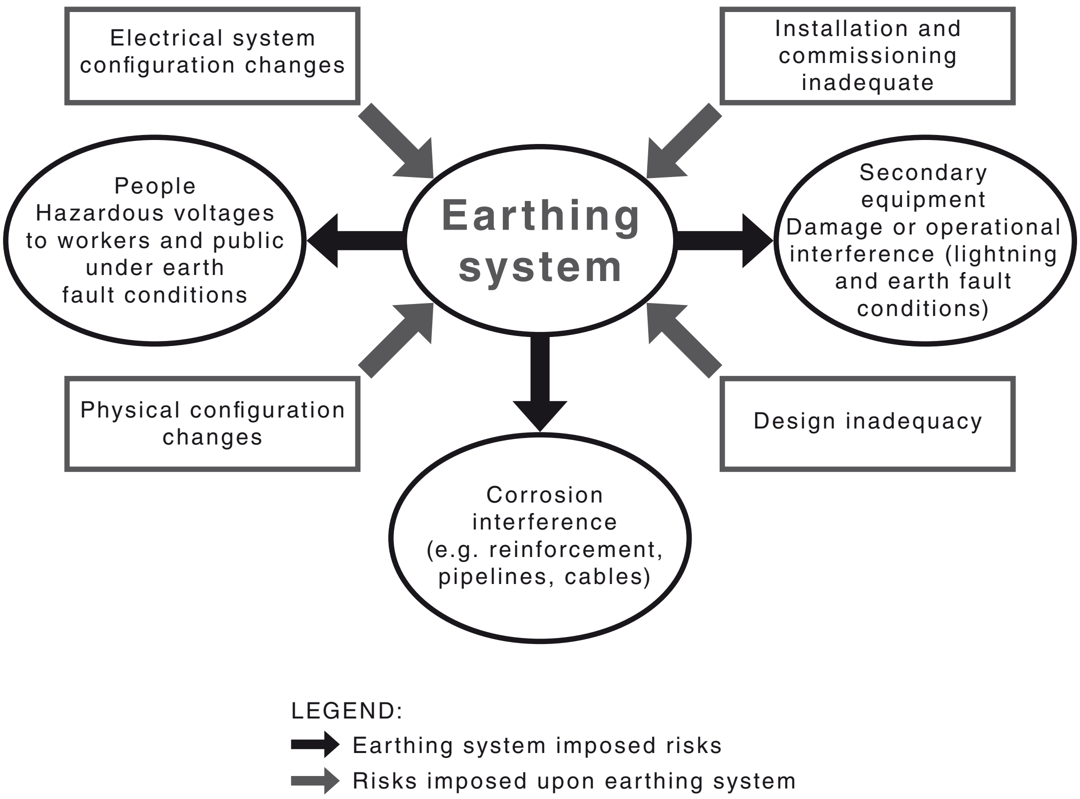
(iii) Controlled access areas (fenced easements or remote areas).

(iv) Series impedance (surface coverings and footwear).

(v) Future possible encroachments upon the electrical network and the effect of system events on those encroachments.

(vi) Conductive and inductive coupling into non-power system plant such as communications infrastructure, telecoms, pipelines and conveyors.

Not all risk is imposed by the earthing system. There are external factors that may also impact upon the earthing system resulting in a change in the risk profile of the installation. Figure 8.3 shows the main risk elements in each category.



NOTE: Substation secondary equipment is associated with equipment such as SCADA, communications or protection systems.

FIGURE 8.3 RISK PROFILES OF EARTHING SYSTEM

The interaction between the substation or powerline earthing systems and secondary systems (e.g. SCADA) also needs to be considered as those systems can adversely affect each other.

8.4.7 Safety criteria for design

8.4.7.1 *Safety criteria*

The effective management of the shock hazard requires an understanding of the ventricular fibrillation (VF) risk and of the following circumstances that make indirect electric shock accidents from earthing systems and earthed metalwork possible:

(a) Current flowing to earth of sufficient magnitude in relation to size of the earthing system and soil resistivity.

(b) Soil resistivity and distribution of earth fault current flow such that voltage gradients are possible at one or more locations.

(c) Presence of an individual at such a location, at a time, and in a position that their body bridges at least two points of different voltage.

(d) Insufficient series resistance to limit the current flow through the body (e.g. skin, shoes, gloves).

(e) Duration of the fault of sufficient time to cause harm at the given location.

As many of these variables are probabilistic in nature (see AS/NZS 60479) there is no simple relation between the resistance of an earthing system as a whole, the maximum shock current to which a person might be exposed, and the likelihood of VF causing a fatality. The process for determining shock safety criteria outlined in Appendix A enables an earthing system designer to allocate limited resources in a manner that provides a level of safety to people corresponding to the probability of a hazard occurring. The analysis recognizes realistic operating conditions and safety constraints in order to provide requirements which are both technically and economically feasible.

Consideration of appropriate safety criteria (usually a shock voltage) is required for all electrical assets that form part of the network. As hazards can be coupled to non-power system plant, particularly during earth faults, consideration shall be given to any voltages created at those locations outside the substations and easements.

8.4.7.2 *Risk quantification and individually derived safety criteria*

The risk profile associated with earthing systems varies greatly for different locations and circumstances. During the first phase of an earthing system design or redesign it is necessary to identify the hazard scenarios applicable to the particular site and power system configuration that could be presented during the period of the project and life of the installation/asset.

Where a design requires that a certain hazard scenario or class of hazard be mitigated and the risk reduction quantified to demonstrate due diligence, the process summarized in Appendix A may be adopted. The ENA Doc 025, EG-0 guide and associated safety analysis software facilitates this process. The application of individually derived safety criteria shall be accompanied by sufficient justifying documentation.

8.4.7.3 *Guidance on standard safety criteria*

The probabilistic method in ENA Doc 025, EG-0 describes a number of standard safety criteria curves that were produced for a given risk level. The scenarios have been selected to cover a number of cases that are commonly met by design engineers within power systems.

The value of the probabilistic method lies in being able to—

(a) identify hazard scenarios where more traditional approaches are non-conservative and more stringent criteria may be justified on account of the risk profile to which the public or operational personnel may be exposed;

(b) identify hazard scenarios where the risk profile is very low and less stringent than previously adopted may be justified; and

(c) more effectively identify which design parameters are contributing to the risk profile. This then allows the designer to undertake a risk cost benefit analysis of the various risk mitigation options.

The risk of these hazards should now be assessed by either aligning hazards with standard contact scenarios in Appendix G (if they meet the boundary conditions) or by assessing the risk associated with a given hazard location identified.

As a guide, representative touch voltage (V_t) limits for a given risk level that may be applied to accessible metalwork for a number of typical cases not covered in the list of Standards and industry guidelines (Clause 8.4.7.4) are shown in Appendix G. The cases covered are as follows:

(i) Residential distribution—includes commercial sites (e.g. shopping centres), and aquatic centres (e.g. public pools).

(ii) Light industrial—sawmill, batching plant, abattoir.

(iii) Large interconnected systems—power stations, heavy industrial, wind turbines.

(iv) Mining—surface plant operations.

(v) Mining—underground coal.

(vi) Mining—underground metals.

(vii) Mining—open cut.

(viii) Mining—road tunnels – construction and operation.

The process in Appendix A should be used to determine the level of hazard associated with voltage limits. The standard safety criteria curves provided in Appendix G are derived using the Appendix A process for a given risk level. For each case study the curve details (figure and equation) and assumptions governing the range of applicability have been included. If the hazard situation under consideration does not meet the case study boundary conditions, the direct probabilistic design approach outlined in Clause 8.4.8 should be performed to assess the risk or generate appropriate design curves.

The following cases are not covered in the Appendix G case studies or the standards in Clause 8.4.7.4 and require case specific design to be undertaken:

(A) Long overland conveyors.

(B) Railway systems.

(C) Theme parks.

8.4.7.4 *Safety criteria within other standards and guidelines*

Safety criteria are provided within other Standards and Guidelines applicable to specific assets or hazard scenarios. Consideration should be given to the following:

(a) Metallic pipeline exposure: AS/NZS 4853.

(b) Telecommunications worker exposure—AS 3835 on earth potential rise (EPR) hazards, SA HB 101 on low frequency induction (LFI) hazards.

(c) Transmission and distribution line hazards: AS/NZS 7000.

(d) Power system plant and substations, and major substations: ENA Doc 025, EG-0.

8.4.8 Perform direct probabilistic design

In the event an identified hazard does not align with a published case study, expected fault and contact scenarios may be used to assess the probability. These can be compiled by using sources of information that may include the following: past fault records, use of models and simulations, practice and relevant experience, published literature, industry data, results of public consultations, and specialist and expert judgment.

All assumptions, boundary conditions, and design decisions determined in the analysis should be articulated in earthing system design documentations.

A direct probabilistic design uses risk boundaries to provide a range for what is considered unreasonable/intolerable and negligible for both individual and societal (i.e. multiple simultaneous) hazard exposures. ENA Doc 025, EG-0 details an approach that enables an engineer or asset owner to assess the need to provide additional mitigation. The use of safety analysis software (e.g. Argon) enables the risk associated with voltages to be assessed for standard conditions or 'one off' situations.

8.4.9 Mitigation/redesign

Although earthing system design procedures involve the installation of a considerable number of risk reducing measures (e.g. protection system, conductor mesh spacing) as part of earthing system design, a range of additional site specific mitigation measures and/or redesign options shall be evaluated. The selection of options should be based upon managing the specific risk associated with the step, touch and transferred voltages for identified hazard scenarios. The principles of the hierarchy of controls should be applied to the mitigation/redesign process in determining priorities (see Clause 2.7).

The following options may be considered for mitigation or redesign (locally or via interconnected systems):

(a) Reduction of the earth impedance of the earthing system.

(b) Reduction of earth fault current using alternative system configurations, e.g. system neutral earthing via resistance or inductance, earth transformer, line reactor.

(c) Reduction of earth return current, e.g. utilizing inductive coupling between metallic cable sheath, earth wire and phase conductor.

(d) Reduction of the fault clearing times.

(e) Interconnection or separation among earthing systems, e.g. impedance connection or separation of HV and LV earth electrodes or systems.

(f) Site relocation.

(g) Installation of gradient control conductors.

(h) Installation of non-conductive materials (e.g. timber or non-conductive poles).

(i) Installation of a barrier fence to limit access.

(j) Installation of a high resistance surface layer (e.g. asphalt or crushed aggregate).

(k) Restricted access or PPE.

(l) Installation of signage.

The design should be evaluated to ensure all reasonable precautions have been included, whose costs are not grossly disproportionate to the benefits. Assessment of risk mitigation is an iterative process to reduce the earthing design risk so far as is reasonably practicable (SFAIRP) or as low as reasonably practicable (ALARP).

Often a combination of the abovementioned risk mitigation treatments may be required. Furthermore, processes, procedures and routine maintenance may be required to ensure the adequacy of proposed mitigation measures. The cost of maintenance over the life of the asset should be considered.

8.4.10 Transient design

Lightning and switching operations are sources of high and low frequency currents and voltages. Surges typically occur when switching reactors, back-to-back capacitors and cables or when operating gas insulated disconnectors. Surges are able to be transferred via transformers. Lightning events, incident either directly or indirectly (i.e. via phase conductors) upon a HV Installation, may cause damage to both primary and secondary plant. Collection and dissipation of the incident energy always involves components within the earthing system. Configuring the earthing system to effectively manage this energy is one task of the design engineers. Additional guidance may be found in AS/NZS 1768.

While earthing of secondary systems may not be the direct responsibility of the HV earthing system design engineer, incorrect coordination with the earthing and grounding of the secondary systems (i.e. protection, d.c. and a.c. auxiliary power and control wiring) may result in the following:

(a) Equipment damage (e.g. relays damaged).

(b) Operational reliability reduction (e.g. false or no CB tripping).

(c) Human safety risk (e.g. fires due to sparking in hazardous areas).

Assessing electromagnetic interference (EMI) sources, coupling mechanisms, interference levels, and resultant physical damage or operational impact regarding the impact of the earthing system configuration, should be part of the earthing system design considerations, as it is always harder to mitigate EMI risks following installation.

8.5 CONSTRUCTION

Earthing system construction generally involves the installation of horizontal, vertical or inclined electrodes, buried or driven into the general mass of earth. Construction may also include connections to cable screens, equipment, structures, fences and OHEWs. During the site construction phase of the project it should be ensured that the physical implementation of the design is compliant and installed/built to an appropriate standard/quality. Unless prescribed otherwise in the design the following recommendations apply:

(a) Chemicals should not be used to alter soil resistivity.

(b) Dissimilar metals should not be used in the earthing system unless corrosion risks are properly addressed.

(c) Special attention should be taken to avoid corrosion where the bare earthing conductor enters the soil or concrete.

(d) Backfill should not include foreign materials.

(e) Installation methods should exclude anything that increases corrosion risk.

(f) The path of the earthing conductors should be as short as possible.

(g) Conductors should be installed with additional protection against mechanical damage during the construction phase (where and as appropriate).

(h) Risers should be given extra consideration for mechanical protection at and around ground level and other exposed points.

(i) Where inspection or testing pits are used, consideration should be given to mechanical protection, corrosion and drainage including during construction.