MEASURES TO REDUCE TRANSFORMER FAILURES IN THE DISTRIBUTION NETWORK OF CEB

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by

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DECLARATION

The work submitted in this dissertation is the result of my own investigation, except where otherwise stated.

It has not already been accepted for any degree, and is also not being concurrently submitted for any other degree.

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3rd February 2011

We endorse the declaration by the candidate.

Professor H.Y.R. Perera

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CONTENTS

Abstract

Ceylon Electricity Board (CEB) has many transformer installations in its distribution network, with their capacities ranging from 100 kVA to 1000 kVA. The latest transformer designs are very much simplified and optimized. Due to the vast spread in the distribution network and practical constraints in employing high end protective devices, these transformers more frequently undergo adverse impacts imposed by the condition of the network and by the nature. These transformers are nowadays manufactured to operate almost without supervision. A high failure rate of nearly 3% per year (out of approximately 20,000 installed transformers) could be observed. When added up the cost due to loss of transformers, the overall loss becomes nearly one billion rupees per year. Although most of the causes contributing for these failures are thought beyond our control, it is investigated and found that this failure rate can be drastically reduced by merely following better erection practices.

This report discusses many causes for distribution transformer failures and elaborates on measures that can be adopted for reducing transformer failures, mainly through proper erection practices.

Existing transformer installations are studied and analyzed to see whether the present auxiliary gear used, lead connecting methods followed and earthing done are acceptable for proper functioning of transformers. It is analyzed and shown that the earthing method practiced presently on MV transformer installations is not effective. A research which has been initiated to determine an improved earthing system is introduced and discussed in this report. Conclusions of this research would be arrived after a careful study.

Studies are carried out to determine the most probable lightning pattern in Sri Lanka and their effects on the distribution network, especially on transformers. A transient waveform simulation is done to observe the voltage stresses exerted on transformers for few selected installation arrangements. This is further expanded to carry out a sensitivity analysis to observe the behavior of voltage stresses under different types of lightning surges. A better installation practice is thereby proposed.

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List of figures

List of tables

Chapter 1

Introduction

1.0 Background

According to the statistics of Ceylon Electricity Board (CEB) in the year 2008, there had been 20,000 distribution transformers installed island wide which were connected to different 11 kV and 33 kV Medium Voltage (MV) networks to supply the domestic and industrial Power demand. These transformers are generally installed outdoor, but few indoor installations also exist. About 600 transformer failures had been reported in the year 2008 [1]. Annual failure rate of the transformers thus becomes 3%. It is observed that this failure rate remains consistent in years 2009 and 2010 as well. Transformer failure rate in utilities worldwide had gone high as 4.5% to 5% in worst situations according to world statistics [6].

According to the present pricing (2010), CEB spends approximately 0.7 million to 3 million rupees [2] for purchasing of a new distribution transformer (depending on the capacity). Transformers with the capacities of 100 kVA and 160 kVA are very common in the distribution network of CEB. These transformers cost 0.7 million and 0.86 million rupees respectively. When considered all other higher capacity transformers fixed to the industrial consumers also, it is reasonable to assume the average loss incurred to CEB due to transformer failures is nearly six hundred million rupees per year. The real cost component can even be more when the hidden cost components such as outage cost, labour cost, transport cost and the related management costs are taken into consideration. Hence an annual estimated loss of one billion rupees can be accounted for transformer failures.

Most of the transformer failures are considered as caused due to lightning strikes; which has to be investigated in detail. It is true that the hitting of a particular lightning surge decides the end of the service life of a transformer, but up to what level it had been deteriorated just before its failure, should be a matter to ponder in a more reasonable manner.

Due to wrong connecting methods, poor earthing methods, wrong selection and usage of protective gear and accessories, bad operational practices (eg : overloading), wrong usage of connectors and poor way leaving practices, CEB transformers extensively undergo deterioration while in service. Early replacement or repair of certain visible defects such as bushing failures and oil leaks from gaskets are also rarely attended to. Modern distribution transformers are designed to operate without routine maintenance, hence oil filtering or silica gel replacement is no more required. This had made the routine inspection gangs to stay away from inspection of transformers. It can be seen that only load readings are taken as a monitoring method and no other monitoring measure is followed.

Although the failure of a transformer is identified as a remarkable loss, there are many other losses that occur associated with its auxiliary gear, which have again a direct impact on proper functioning of the transformers. Few examples are failure of drop down lift off switches, failure of lightning arresters, failure of fuse carriages and theft of copper conductors. Although the cost involved with these looks minor, failure of these cause undue effects on transformers. Theft of copper has become a menace because the transformers without earth leads operate unnoticed until they fail. This can be eliminated if alternate material is introduced for the earth cable. As in the lightning currents, only the skin of the earth cable serves (due to very high rate of rise of the current wave). Usage of copper clad steel for the earth cable can be investigated. As it is not possible to extract copper from copper clad steel, that will reduce theft. Another option would be to draw the earth cable inside the pole, pre cast with a conduit inside. Proper selection and design of auxiliary gear not only saves the cost of frequent replacement of those items but also avoids premature failure of the transformers.

Present practice of CEB is to procure transformers from LTL Transformers (Pvt) Ltd, which is a subsidiary company of CEB. CEB apparently is not keen in keeping any track record on the transformers that are procured and installed. If any manufacturing defect appears, sometimes that may not be identified and the failure is accounted for one due to lightning or some other external influence. It is observed that the manufacturer has optimized the present design to minimize manufacturing costs, which can have detrimental effects on the transformer in the long run. It is found that many transformers that were installed about thirty years ago (in the early 80's) still function very well. These are the designs having big cooling ducts and conservator tanks fitted with silica gel breathers. Amidst very poor working conditions and poor maintenance these transformers survive probably due to the over-designed features applied during that era (see figure 1.1). However, when compared with the population of the transformers with modern design, these olden designs are very rare in the distribution system now.

Figure 1.1 : (A) More than 35 years old CEB Transformer still serving in Bulathsinhala (B) Modern single pole mounted transformer
(Original is in colour)

As the modern transformers are sealed type, no routine oil testing or silica gel replacement is involved (see figure 1.1). However oil sampling is possible through the drain valve if one is keen in monitoring the condition of the oil.

Wrong type of installations can exert undue voltage stresses to the windings during lightning or switching surges, eventually causing the transformer to fail. As the effects to the transformers are worsened due to bad installation practices followed, it is more relevant to pay attention to the installation practices carried out presently.

This report mainly investigates measures to reduce transformer failures in the distribution network of CEB, and suggests simple installation practices that can be adopted to avoid detrimental effects on transformers.

Initially, CEB's transformer installation practices and MV line installation practices are studied. Usage and selection of auxiliary gear having proper ratings is also studied. Values of earth resistances are measured and analyzed against the present earthing methods followed in CEB. To elaborate on this, soil resistivity measurements obtained from few selected areas are analyzed. Improved earthing methods are thereby discussed. Most probable lightning patterns applicable to Sri Lanka are studied with their effects on MV overhead lines and transformers.

Main work of the study is on the analysis of existing lead connection practices used in CEB. After identifying characteristic differences in each arrangement, those are further verified through transient wave analysis. Under the transient wave analysis, transient voltages appearing at various connection nodes and the behaviour of the transformer under various lightning surges, is analyzed using software simulation. Based on the results observed, few proposals are brought up for transformer lead connection.

The objective of the study is to arrive at a reasonably acceptable transformer installation practice so that transformer failures are minimized, saving a huge cost to the CEB.

1.1 Motivation

Annual loss to CEB due to transformer failures is nearly one billion rupees according to the present pricing. Any action taken to minimize transformer failures would directly contribute to a big saving. Also improvements done on the installation practices would lead to find simpler and cost effective installation methods that will reduce labour and material costs and improve life time, thus reducing overall costs associated with transformer installations.

Studies done related to transformer installations will pave the way for finding methods of effective selection and usage of auxiliary gear such as drop down life off switches, arresters and fuses. Proper selection of auxiliary gear will directly contribute to proper functioning of transformers.

Power system is a continuously expanding entity. If not proper solutions are brought at the correct time, adverse situations can aggravate, where finding solutions for those would become a tedious exercise. Being an engineer in CEB, author was motivated to select this topic for his Master's dissertation, as the outcome of this study would be very important to CEB.

1.2 Objective of the study

The objectives of this study are given below.

- Analyze causes for distribution transformer failures in the MV network of CEB.
- Study the present transformer installation practices and suggest improved installation methods.
- Study the characteristics of most probable lightning patterns in Sri Lanka and their effects on distribution transformers.
- Model selected transformer installation arrangements and analyze against different lightning conditions with the aid of software.
- Find a reasonably acceptable transformer installation practice.

1.3 Scope of work

- Common causes for distribution transformer failures in the world are studied, relating the most applicable causes to Sri Lankan context.
- Various transformer installation sites in a selected provincial zone in CEB (Western Province South II) are studied and analyzed. The drawbacks in these installations are noted and improved installation methods are proposed.
- Earthing methods practiced presently on MV transformer installations are analyzed to see whether those are effective. Research work that has been initiated for finding an effective earthing method is discussed.
- Most common lightning patterns in Sri Lanka, characteristics of the lightning currents and their effects on MV network are studied, giving prominence to their effects on distribution transformers.

- Few existing transformer installation arrangements and proposed installation arrangements are modeled using PSCAD software.
- Simulated and analyzed each installation arrangement with different lightning surges to observe the behaviour of voltages at the critical connecting nodes.
- Based on the outcome of above results, a reasonably acceptable transformer installation method is proposed.

Chapter 2

Causes for transformer failures

2.0 Voltage stresses

Voltage stresses can be divided into two areas namely sustained stresses and intermittent stresses. Further it can be classified into stresses occurring from LV side and from HV side.

Sustained voltage stresses at the LV side can happen through wrong HV tap selection and voltage imbalance. Intermittent and transient voltage stresses at HV and LV sides can happen due to intermittent earth faults and from induction of lightning surges. Intermittent earth faults are very common due to touching of trees.

Distribution transformers undergo transient over voltages. These can happen from direct lightning strikes or through induced lightning strikes on MV or LV networks. This type of stresses can result in insulation failure, inter tern short circuiting of windings and winding to earth faults. The severity of the over voltage is decided by the rising rate of the involved current, that leads to uneven distribution of stresses in the windings, thus on the insulation.

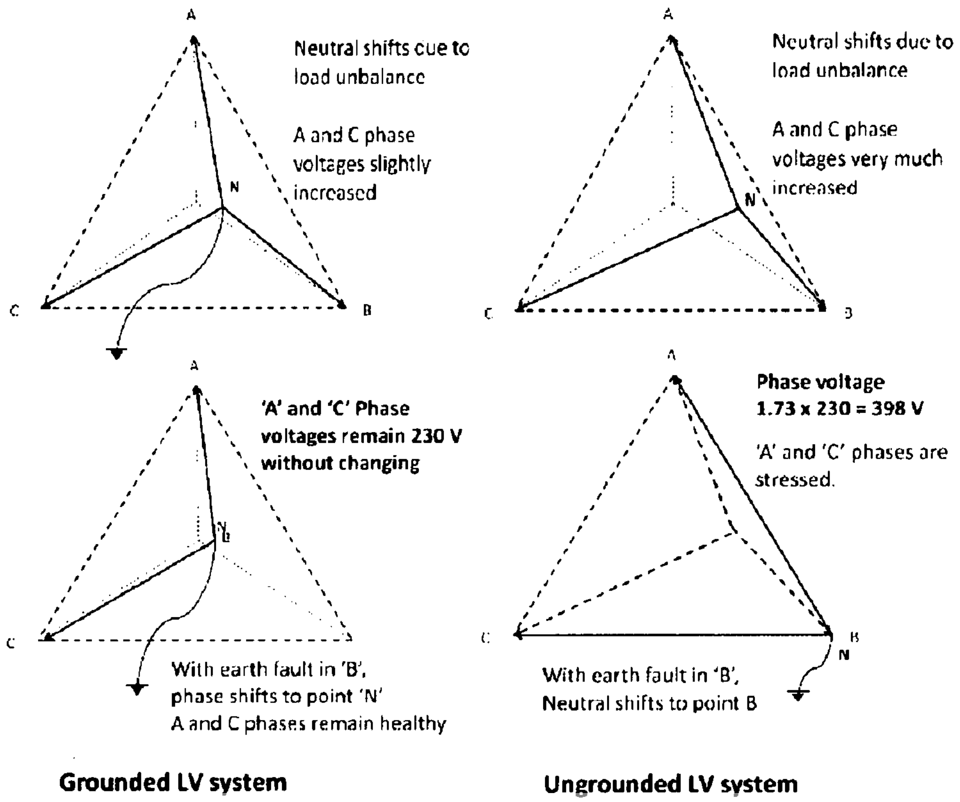
When surges occur on a MV system, it can flash over creating a 'chopped wave transient'. The very high decreasing rate of the current in a chopped wave causes to create a very high voltage on the line. If the basic impulse insulation level (BIL) ratings of the connected transformers are exceeded, transformer failure is very likely. Transformers must be provided with lightning arresters to withstand various types of surges that are likely on the MV system. It must be noted that rated insulation level of a transformer also decreases with time, due to ageing. The quality of the lightning arresters connected on the system also matters. Distribution class lightning arresters are used in the MV system. As lightning arresters deteriorate with time, their condition has to be ascertained in order to ensure maximum protection of the transformer. In CEB's distribution sector, no action is taken to monitor the condition of lightning arresters. Thermal imaging is done in other utilities to detect arresters before they fail. As deteriorating arresters' leakage current increases, it creates a temperature increase, which can be monitored easily by thermal imaging.

Overhead earth wire of the MV installation plays a big role in damping the lightning surge occurred on the MV line. On the other hand it reduces the insulation level of the MV line, creating possibility of frequent flashover. Although this lowers the insulation level causing more flashovers, as far as transformers are concerned, the presence of the overhead earth wire is for the betterment. CEB's practice is to draw the earth wire under the three MV phase conductors in pole lines, with all cross arms connected. This is acceptable when the MV feeders are running in a more shielded path at a lower exposure level having surrounding trees and buildings. Under such exposure levels the probability of inducing higher lightning surges on the MV system is low. Any induced surge on the MV wires will be effectively damped through the electromagnetic coupling with the overhead earth wire. Direct striking of lightning on the conductors is very unlikely in a shielded path. However when MV circuits run along paths with higher exposure levels, having the earth wire under the MV lines will not contribute much effectively in shielding lightning surges. MV lines running along exposed paths such as bare lands, clear road sides and paddy fields are highly vulnerable for direct striking of lightning surges, hence the role of the overhead earth conductor should be more as a shield wire rather than surge damping. Hence it will be more effective if the overhead earth wire is drawn at the top of the pole when the circuit runs along exposed pathways. In the past, the earth wire had been drawn above the phase conductors, but those have broken and fallen on live conductors causing frequent tripping. This had happened due to poor maintenance and poor usage of proper connectors. Rather than addressing the real cause, eventually CEB had deviated to the present practice where the earth wire is drawn under the phase conductors. In tower line MV constructions still the earth wire is drawn at the top of the tower. Due to proper selection of material and proper maintenance, this has not caused any problems.

Lightning surges can get induced on the LV system through electromagnetic coupling. In addition to the direct influence by the lightning surge itself, this may be due to the coupling with the medium voltage (MV) lines, through the overhead ground wire, or through transformer stray capacitance. Also lightning surges can penetrate into the LV system through the neutral earth's ground coupling if proper distance is not maintained with the MV side lightning arrester's earth. When laying out lightning arrester earth and LV neutral earth conductors along the pole, it is necessary to pay attention to lay those conductors preferably at the either sides of the pole or as much as away from each, to avoid electromagnetic coupling. Also the LV earthing system must be made at least 3 m away from lightning arrester earth, to avoid coupling through soil. If not done so, lightning surge currents that are diverted to the ground through the arrester's earth wire can penetrate into the LV neutral and induce high voltages in the LV side. This can again cause insulation failures in the transformer or induced surges in the LV distribution system. There is also the possibility of lightning directly hitting LV wires, in exceptional situations.

LV voltage unbalance can cause sustained stresses. Unbalance in loading can be a reason for this. Load balancing is done by CEB mostly based on the loading data collected at the peak hour, which falls between 7 pm to 10 pm. It is found that loading pattern of the consumers change from day time towards the peak time, so that any balancing carried out based on the peak hour's data can cause unbalance during the non-peak day time. Also if the neutral earth cable is absent or the neutral earth is weak, unbalance becomes more severe. This situation can be worse if a phase to earth fault happens at the LV side, where the voltage of the healthy phases can reach upto the line voltage (see figure 2.1).

When the LV neutral earth is weak or absent, if any intermittent phase to earth fault happens, that can generate very large voltages in the magnitude of six to eight times the nominal voltage at the healthy phases. This is due to the persisting arc at the ground fault location and high frequency current oscillations associated with. These types of faults are commonly caused by touching of plants and trees. When an arc is established, even if the branch that caused the earth fault is burnt out, the arc created persists for a longer duration than expected, due to ionization of the surrounding air. This phenomenon is called 'arcing ground', which is very harmful to the transformer's winding and insulation. As the 33 kV HV network is not a solidly earthed system, again if the ground fault is arcing or intermittent type, there is possibility of having very high transient over voltages at the healthy phases. These transients at the HV side can cause fatigue on insulation and subsequent failures in the insulation system of the transformers, leading to extensive damages.



Grounded LV system

Ungrounded LV system

Figure 2.1 : Effect of phase earth faults in LV systems with and without neutral point earth

2.1 High Switching and short circuit currents

Distribution transformer operation involves intermittent energizing and de-energizing. This is due to circuit breaker operation at the grid substations or auto-recloser operation. Rapid operation of the breakers causes fast collapse and build of the flux in the magnetizing core of the transformer and causes high inrush currents to flow in. High inrush currents cause huge forces applied on windings and structure that possibly reduce the lifecycle of transformers. Since this happens with the loads connected at the LV side, transient inrush current of a transformer can peak upto its short circuit current's magnitude [3]. This type of behaviour is common and unavoidable in retail distribution systems. In the bulk distribution (whereas mostly in the industrial sector) this type of operations can be made to happen in a more organized manner. Any transient load current oscillations that can happen with the energizing of the transformer can be damped in bulk supply systems by proper switching of the loads. However damping of the switching currents is related to the transformer's magnetic characteristics; hence the presence of a load has less effect [4]. This type of operating stresses is detrimental to the transformer and affects the lifetime of the transformer.

Transformers feed short circuits continuously if proper fuses are not employed for fault isolation. When a phase to earth fault occurs at the LV downstream side, the earth loop impedance becomes important in deciding the associated short-circuit current. If the fault happens far from the transformer, the short circuit current can have few amperes which may not fuse the faulty circuit at all. Faults occurring near the transformer have high fault currents, thus exert significant stress on the winding, if proper fuses are not employed. In most of the transformer locations of CEB, it can be seen that wires are used in place of proper fuses in the LV distribution panel. Generally the transformers we use have roughly 4% short circuit ratio, which means it can handle 25 times its nominal current for a short duration. A low voltage fault near the transformer causes thermal stresses until it trips and also mechanical stresses due to the electro dynamic effect when the fault first appears [4]. Although transformers are generally designed to withstand short-circuit faults across their terminals, repeated faults can have a cumulative effect causing coil displacement and premature ageing.

2.2 Overloading

If a transformer draws a higher current at the LV side than its rated current, it is an overloaded condition. Transformers are designed to operate overloaded within given constraints, usually for short periods. If a transformer is continuously overloaded, it can contribute to deterioration of winding insulation due to continuous heat generation at the windings and hot spots. With ageing, a transformer's overloading capability decreases. CEB's practice is to consider replacing the transformer with a higher capacity transformer when the transformer's peak load exceeds 80% of the rated load. However it is still common to find overloaded transformers in certain areas in the CEB network.

2.3 Transformer ageing

With ageing of transformers, its insulation weakens and minor electrical breakdowns initiate. This can further aggravate until a permanent breakdown occurs. The primary causes for this insulation breakdown may be mechanical, chemical or thermal reasons.

In the low voltage side of the transformers, winding coils are copper sheets which are wound with insulating paper in between the coils. In addition to the coil and insulating paper, there are barriers (press board) which are also made out of craft pulp.

Wood and iron is used as structural materials and all these are immersed in insulating oil. Over voltages in the windings (especially in high voltage coils) can cause small partial discharges between winding spacers, which can aggravate if the insulation is weak.

Transformer insulation becomes weak due to presence of moisture and heat. Irrespective of other influences, merely based on the moisture content and average operating temperature of insulation paper, transformer's life expectation can be estimated through the empirical curves (figure 2.2).

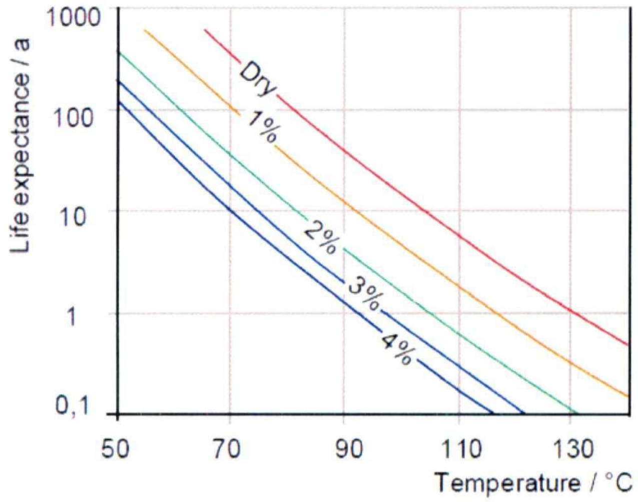


Figure 2.2 : Ageing curves of insulation paper with moisture [23]
(Original is in colour)

Moisture absorption into the paper/oil medium can happen through weak packings and gaskets. Loading and de-loading of the transformer causes relative heating and cooling of the tank structure, causing the transformer tank to expand and contract.

This causes air to breath-in through the weak gaskets. Air contains moisture, thus insulating oil absorbs this moisture and becomes weak. Once minor insulation breakdowns occur by partial discharge, further insulation degradation can happen due to formation of impurity compounds through the reactions happening inside the transformer tank. These compounds get deposited as mild sludge particles between windings, reducing the dielectric properties of the insulation and this supports further partial discharges at higher voltages. Transformer winding hot spots are formed in this manner. Hot spots are an indication of partial discharges between windings or mechanical stresses in the windings. These can exhibit even at the nominal operating voltages under worst condition.

These chemical reactions cause the paper insulation to degrade further. Old insulation paper also produces moisture when they degrade [23]. With the weakening of the insulation paper, their degree of polymerization (DP) reduces causing the cellulose grains to become very much apart. Subsequent effect would be reduction in the tensile strength of the insulating paper. Then the cellulose particles can escape from the main medium and add with the oil to form sludge. Electrical sparks in the sludge medium makes transformer oil more acidic which again affects its metal parts (structure, copper windings and tank) to corrode. All these are detrimental effects to the transformer, which finally increases the moisture, acidity and sludge levels in the insulating oil, decreasing the dielectric strength of the insulation [5]. A transformer which has weak insulation can fail instantly due to any external influence such as a switching surge or an induced surge. Hence, the life expectancy of transformers is directly related to the insulation quality as in figure 2.2.

2.4 Incorrect installation practices

As discussed in the introduction, incorrect installation practices worsen all above effects by resulting undue voltages to appear on winding and insulation. This causes the transformer to deteriorate very fast. Hence, wrong installation practices again support ageing and premature failure of transformers. Modern distribution transformers are sealed type and are not designed to carry out oil re-conditioning. Thermal expansion and contraction of the tank is met by the bellow action of the tank's corrugation, hence silica gel breather is no more employed. If there is no provision for moisture ingression and if quality materials are being used during construction, the quality of the insulating oil can be guaranteed for a considerable period.

However still the windings can undergo voltage stresses. Voltage stresses can be caused by various reasons. Voltage stresses can appear on the LV side as well as on HV side. Both are detrimental to the transformer.

Due to the wrong selection and wrong erection practices of auxiliary gear such as drop down lift- off switches, lightning arresters, connectors, etc. also transformers undergo stresses. It is seen that when selecting DDLOs proper attention is not given on their ratings. Most of the DDLOs employed in the MV system of CEB are under rated ones merely due to misinterpretation of the manufacturer's ratings. It is seen that most of the USA manufactured DDLOs come with the ratings suitable for solidly grounded MV systems. The Sri Lankan 33 kV medium voltage distribution system is not solidly grounded, but indirectly grounded system. When erecting DDLOs, proper care should be taken to maintain sufficient clearance from the cross arms and structures. There are many DDLO insulator failures reported due to not maintaining clearance with the cross arms. Flash over of surges can occur from DDLO to the cross arms in such installations. When it happens in a transformer DDLO, an undue voltage can develop on the transformer's body through structural connections, causing stresses on the insulation between tank and winding. This is not happening if the surge travels along the intended path as far as lightning arresters are employed for proper surge diversion.

Proper selection and erection of lightning arresters also matter in protecting the transformers. Lightning arresters have to be selected with suitable technical knowledge to ensure the transformer is satisfactorily protected. When selecting lightning arresters, proper attention must be given to the factors such as discharge current rating of the arrester, residual voltage of the arrester, maximum continuous operating voltage (MCOV), duty cycle rating (rated voltage), temporary overvoltage (TOV) characteristics and energy handling capability. Since CEB's 33 kV medium voltage system is an indirectly earthed one, when an earth fault occurs on one phase, other healthy phases' voltage can rise considerably. As in an unearthed three wire system, it is not reasonable to expect phase to ground voltage on the healthy phases to rise near the line voltage, because system has an indirectly employed earth at the grid substation. However this voltage rise has to be estimated based on reasonable assumptions. In indirectly earthed systems single line to ground faults carry low fault currents, hence tripping mechanisms will not trip the circuit instantly and will allow the fault to sustain for a longer period. MV earth faults involving low fault currents sustain without tripping the circuit because of the set sensitivity settings of the relays. Hence, it is necessary to select arresters with an MCOV rating suitably decided on the MV system's behaviour. This behaviour will change during the rainy season where the wet trees and wet soil conduct well, thus the fault current is mostly high enough to trip the MV circuit.

It is found in transformer installations, earth resistances are greater than what it should be. It must be ensured that the earth resistance is within the acceptable limit (less than 20Ω) to have proper protection of the transformer [7]. In CEB's installation practice, now mostly practiced grounding method is the concreted mesh method (see figure 2.3).

Figure 2.3 : Concrete Mesh Earth (A) Mesh before concreting, (B) Mesh inserted into the ground pit before concreting
(Original is in colour)

It has shown that by putting this concrete block, earth resistance is drastically reduced compared to that of a single rod earth, but still it is showing unacceptable higher readings. The mix of the concrete used is the normal construction mix. Since the strength of the earthing structure is not the prime requirement, this mix can be revised. A study is initiated on this which is described in chapter 3. In this study, kind of 'conductive concrete' is experimented with commonly available material.

Use of proper material for connectors matter for the trouble free operation of transformers. Basically in the earth leads, connections have to be avoided as far as possible since the connections introduce higher inductance that will generate very high voltages during the surge current diversion. Connectors (bolts, nuts, crimping connectors, etc.) used should be of the proper material. Use of unsuitable connecting methods at the copper earth cable to grounding rod connection can cause galvanic corrosion at the joint and weaken the connection with time, causing high resistance at the joint. During surge diversion very high voltages can appear at these joints, causing the transformer insulation to undergo very high stresses.

Chapter 3

Transformer installations

3.0 MV and LV network configuration of CEB

CEB's distribution system is a 33 kV three phase system with the HV side of the transformer indirectly earthed at the grid substation via the earthing transformer. 11 kV systems also exist with the primary side of the transformer solidly earthed at the primary substations (the term 'primary substation' is widely used in CEB for the secondary step down level: 33 kV to 11 kV).

Distribution transformer's HV primary is delta connected and the secondary LV distribution side is star connected with its neutral earthed once at the transformer installation (T-T configuration). Consumer is supplied with the 400 V secondary distribution lines run overhead (see figure 3.1). The consumer's protective earth and the transformer's LV neutral earth provides a fault current path through the ground upto the supply transformer in case of earth fault, until the house hold protection activates and trips the circuit. LV distribution circuits running from the transformer are connected through LV fuses to prevent overloading of the transformer. These fuse cutouts are fixed onto the transformer pole itself.

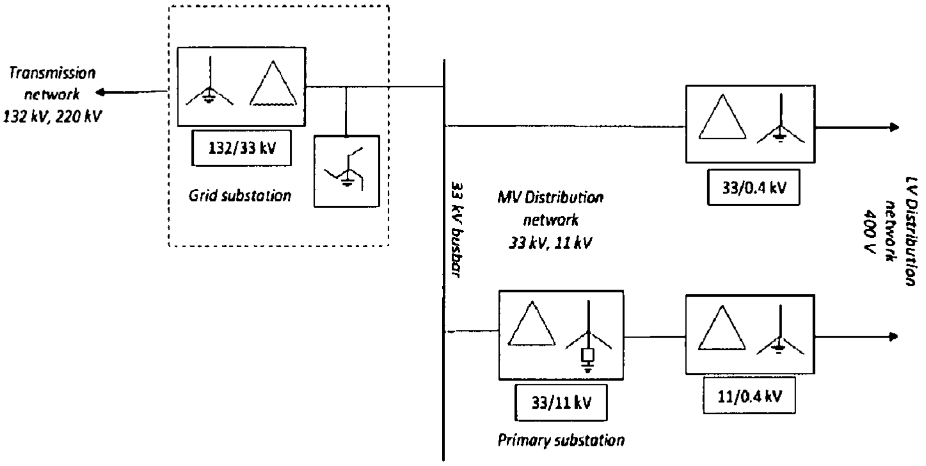


Figure 3.1 : Distribution network configuration of CEB

Although underground cable distribution systems also exist in CEB, (mainly around Colombo city limits) the installation practices used there are not discussed here.

Mostly the MV and LV lines run overhead, on concrete poles. MV lines are drawn in horizontal or vertical configuration on steel cross arms fitted with insulators, while the LV lines are sometimes drawn under the same MV poles, with additional LV poles erect in between. LV circuits may run deviated away from the MV line, along residential areas to supply the public demand. Lattice tower type poles and wooden poles are also used depending on the erection constraints of the terrain.

3.1 Transformer installation practices in CEB

Transformers are connected by tapping off from the MV lines, through a drop-down lift-on (DDLO) fuse switch mounted on the same pole. Separate lightning arrester cross arms were installed for mounting lightning arresters, until very recent. Now the distribution transformers are supplied with a lightning arrester bracket mounted on its tank itself. Transformer installations can be identified as single pole mounted, double pole mounted and concrete plinth mounted types. 100 kVA and 160 kVA transformers are usually single pole mounted types. 250 kVA transformers are double pole mounted and above 400 kVA (mostly for industrial consumers) transformers are constructed on concrete plinths with protective fence. A typical transformer installation is shown in figure 3.2. When investigated CEB's MV transformer sites, it can be found that different installation methods are practiced.

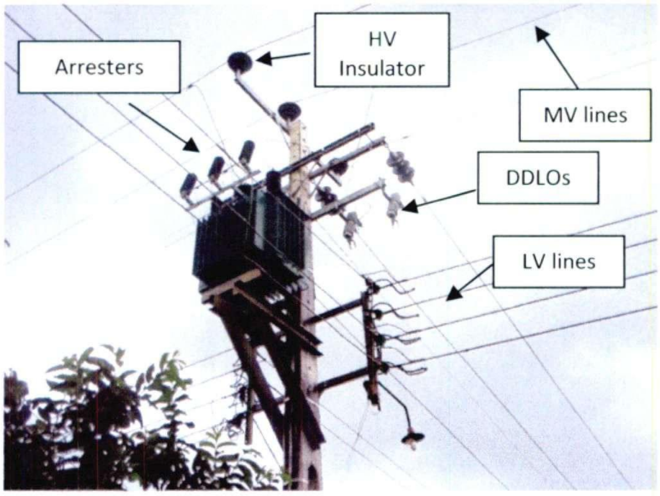


Figure 3.2 : A Typical single pole transformer installation
(Original is in colour)

Few transformer lead connection practices found from the field observations are discussed below.

In transformer installations, in addition to the two earths (arrester earth and LV neutral earth) sometimes it can be seen that the overhead shielding earth wire earthed separately or together with the arrester and transformer tank earth. In very old transformer installations, it can be seen that the old cast iron earth pipe is still used for connecting the overhead earth wire, while new earth blocks are employed for neutral and arrester earth. Big differences could be seen in the way the arrester and transformer body earth cables are connected. These are elaborated in figure 3.3. Overhead earth wire connection is not shown here as it is mostly connected to the arrester's earth, through the structural connections. There are many ways of connecting arrester, tank and neutral earths. These installation practices have impact on lightning surge protection of the transformer to a great deal [8].

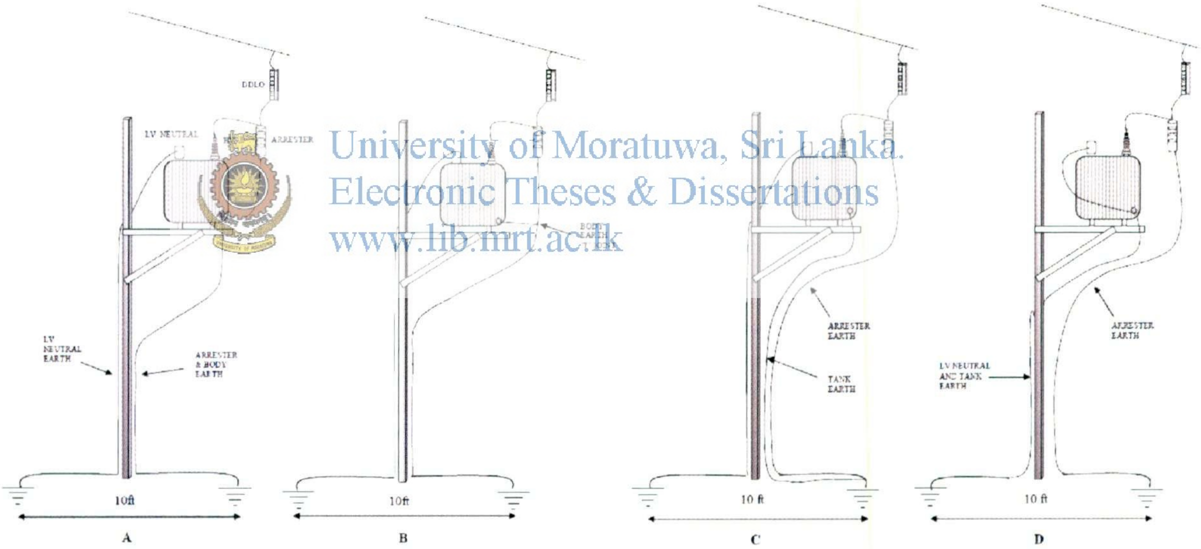


Figure 3.3 : CEB's transformer installation practices

Method 'A'

The bottom terminal of the arrester is connected to the transformer tank at the tank's earth connecting flange. Arrester earth wire runs from there along the pole to the ground electrode. LV neutral is separately earthed. In this practice, improper material had been used for connecting the arrester lead wire to the transformer tank, without giving concern to bi-metallic corrosion. Hence the connections fail at this point, with time. This led to a misconception that this method is bad and the method 'C' had been followed later on.

Method 'B'

Arrester's bottom terminal runs directly to the ground electrode. The transformer tank is connected to this lead as a 'T' connection, using a proper copper 'C' type compression clamp. This method was introduced about two years ago, before the introduction of transformers with arrester bracket mounted on its tank. The intention was to minimize the lead length (see also section 4.3.1). LV neutral earth is done the same way as in the method 'A'.

Method 'C'

After rejecting method 'A', method 'C' had been adopted and followed. Here the arrester end terminal runs to the earth electrode separately and the transformer tank is connected with a separate lead. Both earth leads connect at the ground level, to the earthing electrode. Here also the LV neutral earth remains unchanged as done in the previous methods. This method has the highest lead length, which is not desirable.

Method 'D'

The arrester earth lead connects the earth electrode separately. LV neutral first connects the transformer tank and then the LV earth electrode. In all above methods, the distance between the LV and MV grounding electrodes is maintained around 10 feet (3 m). The idea is to keep the effective earth volumes separately so that the ground coupling is minimized. In very rare cases the MV tap off line for the transformer first connecting the transformer HV terminal and then connecting the lightning arrester's terminal. The drawback of this connecting method is the involved lead length that exerts higher voltages on the insulation (see section 4.3.1).

3.2 Earthing methods

3.2.1 Earth resistance

For effectively dispersing the lightning surge current, earth impedance has to be brought to an acceptable level. It is found in most of the transformer installations earth resistances are greater than what it should be. It must be ensured that the earth resistance is within the acceptable limit (less than 20Ω). Presently a meshed concrete block is used for earthing at the transformer installations. The principle behind this is the improvement of critical soil volume that influences mostly for the earth resistance. From the figure 3.4 it is seen that the soil beyond a distance roughly equal to the rod length, do not contribute to improve the overall earth resistance. In order to get the plateau of the curve further down, a practically possible soil volume is selected and treated. This is shown as the critical soil cylinder in figure 3.4. CEB uses a steel mesh with 60 cm in diameter and 110 cm in height with the copper clad earth rod inserted in the middle. This is placed inside a pit dug on the ground, and concreted. Diameter of the concrete block becomes roughly 80 cm.

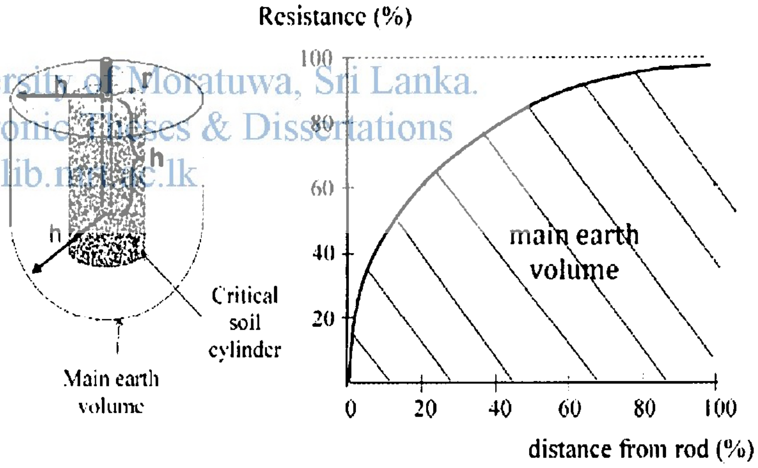


Figure 3.4 : Illustration of critical soil volume
(Original is in colour)

In the concrete mixture granite and sand contributes for higher resistivity while the cement contributes for lower resistivity. Soon after concreting, the earthing system can exhibit low earth resistance because of the presence of moisture in the concrete. This condition can diminish with time, causing the resistance to become high. Few earth resistance readings taken from concrete block earths are shown in the table 3.1. For comparison purpose, single rods were also inserted and readings taken. It is noted that the newly inserted single rod readings are high. This is due to poor contact with the soil. These readings will obviously drop with time when the soil settles.

Installation site	Top soil resistivity (Ωm)	Earth resistance with concrete block (Ω)		Earth resistance with single rod (Ω)	
		Theoretical	Practical	Theoretical	Practical
Jayawadanagama	220	60	84	155	298
Munagama	225	61	40	159	218
Peragashandiya	340	78	60	240	243
Illimba	380	83	62	269	281
Ratiiyela	270	67	61	191	311
Milleniya	180	54	39	127	236
Assumed soil	*100*	*35*		*70*	

Copper rod diameter 17 mm, length 120 cm
Concrete block diameter 80 cm, height 110 cm (with copper rod inside)
Resistivity of concrete assumed to be 50 Ωm for the theoretical calculation

Table 3.1 – Soil resistivities and earth resistances with the concrete block and single rod

When compared the practical readings obtained, it is seen by using concrete block earth, earth resistance is remarkably reduced compared to a single rod earth. However it is still higher than what is expected to have in a transformer installation. It is recommended to have at least 20 Ω earth resistance in a transformer installation. It is calculated to compare the earth resistance with single rod and concrete block for a hypothetical soil having resistivity of 100 Ωm. The theoretical value obtained for the concrete block earth shows that the earth resistance would come somewhat within acceptable range only for soils having resistivities below 100 Ωm. This proves that the presently used concrete block would not give acceptable earth resistance, because most of our soils are having very high soil resistivities than 100 Ωm. Paralleling of the blocks would improve the resistance, but it has many practical constraints when installing earths in the urban and suburban areas due to space limitations. Also the cost would be considerably high if paralleling of concrete blocks is to be done.

3.2.2 Soil resistivity

In order to determine the suitability of the presently used earthing method, soil resistivity has to be known. Soil resistivity profiles are obtained at different places with high lightning activity, using Wenner's four point method. Results are plotted in the figure 3.5.

It is seen that most of the sites are having multi layer soil profiles (eg : Illimba, Munagama, Malabe). Top soil resistivity matters for the measured earth resistance. We could observe the top soil resistivities (at low probe distances) are around 200 Ωm to 400 Ωm in Illimba and Munagama sites while Malabe, Horana Town and Piliyandala sites exhibit low resistivities (around 50 Ωm to 150 Ωm). Due to geographic reasons, most lightning prone areas are having higher soil resistivities (rocky soils). Hence the suitability of the present earthing system is questionable. An improved earthing method has to be investigated. Studies are in progress on different earthing methods that can be adopted.

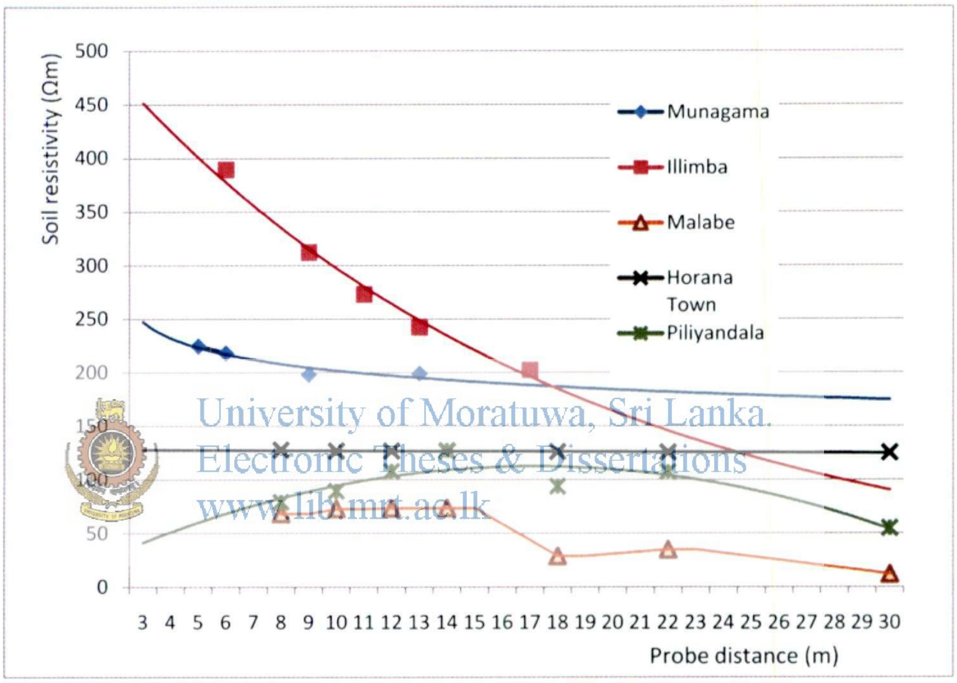


Figure 3.5 : Soil resistivity graphs (20% moist soil)
(Original is in colour)

3.2.3 Improvement on earthing methods

For proper dispersion of the lightning current, impulse earth resistance matters. Soil resistivity conventionally measured using DC currents gives a picture of the condition of the soil, but does not reflect the exact behaviour under the transients. Giving concern to the transient property of the surge current, few earthing sample designs are proposed. Main features of these samples are increased and smoothened surfaces of the critical earth cylinder, improved conductivity of the critical earth cylinder, use of conductive cement mixture, improvement of the horizontal conductor profile and avoidance of joints.

Various locally available material such as graphite, coal powder, bentonite and red soil are mixed in different proportions into the concrete, to obtain few samples for testing. Drawings of the layout profiles are shown in appendix III, IV and V.

General layout is such that a 3 m long copper conductor with its insulation removed, is laid horizontally about 400 mm under the soil and covered with the conductive cement mixture upto a level as shown in appendix III. Then it connects to a pre-cast concrete cylinder (with diameter 150 mm and height 1.2 m) which runs vertically into the earth. The earth is bored before inserting this cylinder, and then gaps are re-filled. Different variations are done in different samples. Basic features of the test samples are described in the table 3.2.

The new designs are made in such a manner that can be pre-cast and transported to the site. This makes installation much easier and time saving. For the initial phase of the study, concrete cylinder's diameter is taken as 150 mm. It is expected to do a comparative in detail study later on the samples laid, and to establish the appropriately suitable cylinder size and material composition.

Sample earth designs are installed at a site selected in Horana. It is planned to obtain earth resistance readings of these sample earths in long term on monthly basis and to plot with the rainfall data to observe their variation pattern with the environment conditions. This part shall be undertaken in a future project. It is suggested to unearth these samples after a considerable period (say 2 years) and to observe their cathodic sacrificial rate and other reactions taken place on copper electrodes and cables to determine the durability. Also it is needed to carry out a safety assessment on the selected layout methods with respect to ground potential rise and associated step potential. This will need to be done by taking into consideration the most probable lightning patterns and the selected sample profiles.

Soon after concreting, some earthing systems can exhibit high earth resistance because of poor soil coupling. In some cases it may exhibit low resistance due to the presence of moisture. These change with time with the environmental conditions. As most of the above readings were initially taken soon after installation before the soil settles down, distorted readings have resulted. This is clear when compared with the readings taken after one month (see table 3.3). Appendix I shows the photographs of sample earths being laid and other experimental earthing systems tried out.

Sample	Proportions of the conductive mixture	Description
A	Cement 1 : Sand 2 : Granite 4	Normal concrete mixture for horizontal part and for cylinder. Conductor and rod exothermally welded
B	Cement 1 : Sand 2 : Granite 4: Graphite 0.25	Normal concrete and graphite mixture for horizontal part and for cylinder. Conductor and rod exothermally welded
C	Cement 1 : Sand 2 : Granite 4: Bentonite 0.25	Normal concrete and Bentonite mixture for horizontal part and cylinder. Conductor and rod exothermally welded
D	Cement 1 : Sand 1.5 : Granite 3	A different concrete mixture with less granite and less sand for horizontal part & cylinder. Conductor and rod exothermally welded
E	Cement 1 : Sand 1.5 : Granite 3: Barbeque charcoal powder 0.25	Different concrete mix with barbecue charcoal powder for horizontal part and cylinder. Conductor and rod exothermally welded
F	Sieved soil 2 : Cement 1 : Granite 3	Concrete without sand, only sieved soil and cement for horizontal part and cylinder. Conductor and rod exothermally welded
G	Cement 1 : Sand 2 : Granite 4 : Coal powder 0.25 (horizontal part), Cement 1 : Sand 1.5 : Granite 3 (cylinder)	Two different mixes for horizontal part and cylinder. Conductor and rod exothermally welded
H	No concrete	Earth rod driven into ground without concrete and insulated horizontal conductor part inside ground. Conductor and rod exothermally welded
I	No concrete	Earth rod driven into ground without concrete and bare horizontal conductor part inside ground. Conductor and rod exothermally welded
J	No concrete	Same as (I) with longer horizontal length (l = 4000 mm). Conductor and rod exothermally welded
K	No concrete	Horizontal bare copper tape (25 mmx 3mm x 3000 mm) without any concrete, no cylinder
L(1)	Cement 1 : Sand 1.5 : Granite 3	Concrete mix as in sample D, bare conductor continuing horizontally and vertically inside the cylinder, without joints.
L(2)	Cement 1 : Sand 1.5 : Granite 3	Concrete mix as in sample L(1), with single bare conductor continuing horizontally and vertically inside the cylinder without joints. Strands made in rectangular meshed profile inside the cylinder.
M(1)	Cement 1 : Sand 1.5 : Granite 3	Bare conductor instead of rod, inside the cylinder. No horizontal part
M(2)	Cement 1 : Sand 2 : Granite 3: Graphite 0.25	Same as M(1), different concrete mixture
M(3)	Cement 1 : Sand 2 : Granite 3 : Graphite 0.33 : Bentonite 0.33 : Charcoal powder 0.33	Same as M(1), with the strands inside the cylinder made to a rectangular meshed profile. Different concrete mixture
M(4)	Sand 2 : Graphite 1 : Sieved soil 8	No cement. Mix filled and compressed to the earth pit and bare conductor inside the earth cylinder with strands made in rectangular meshed profile. No horizontal part

Table 3.2 : Earth models used for research study

Model	Date commissioned	Earth resistance value (Ω) as at 14.12.2010	Site condition on 14.12.2010	Earth resistance value (Ω) as at 17.01.2011	Site condition on 17.01.2011
A	24.11.2010	175	Model earths 'A' to 'G' and 'M3' installed after heavy rains. Readings taken after rain seized. Expect moisture content of soil to be 25% - 30%. Soil resistivity of the site was 125Ωm	176	One week after rains & unusual climatic change (La-Nina effect). Taken on a Sunny day. Moisture content of soil approximately 20%
B		123		109	
C		145		158	
D		167		174	
E		159		159	
F		150		206	
G		196		206	
H	13.12.2010	748		700	
I		436		378	
J		513		425	
K		665		410	
L(1)	14.12.2010	157		166	
L(2)		258		217	
M(1)	13.12.2010	513		349	
M(2)		479		391	
M(3)	24.11.2010	142		160	
M(4)	14.12.2010	231		201	

Table 3.3 : Earth resistance measurements of the model earth installations

Chapter 4

Lightning surges

4.0 Typical lightning surge

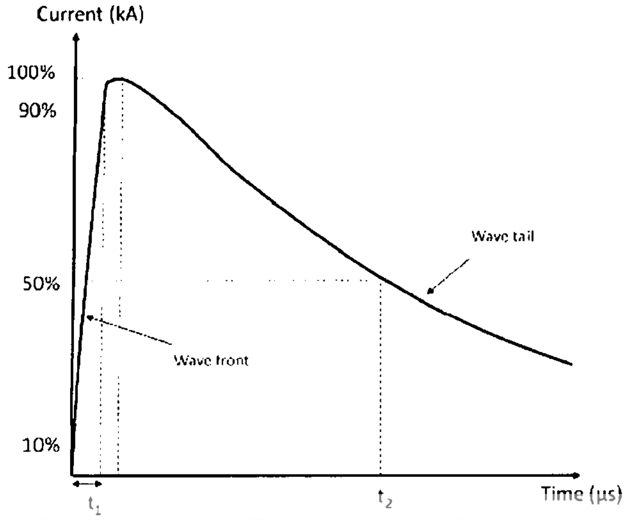


Figure 4.1 : Lightning surge current waveform

Since 1936, experiments had been done to determine the shape of the lightning current. It had been measured and established the lightning surge current waveform as shown in figure 4.1. Although shown customarily with a positive peak, mostly it appears with a negative peak due to the nature of thunder cloud discharge. In IEEE standard 4 – 1995, time taken to reach the peak value of the wave is defined as the time taken to rise 30% to 90% of the peak, and the tame taken to reach half of the peak is measured from 30% origin [7]. This is different in IEC standards, where 10% is taken instead of 30%, as shown in figure 4.1. Since 30% or 10% of few micro seconds is a very small value, it is fair to assume a zero origin in most of the waves. Time taken to reach the peak from zero origin is described as 1.25 times t_1. Expressing the rise time of the lightning current in this manner is solely due to the constraints in measurements. Lightning wave is denoted with its magnitude and (t_1, t_2) durations in micro seconds.

It is found that a lightning flash has more than one stroke. Ionization of the lightning path by the first stroke supports subsequent strokes. Statistically 50% of the lightning flashes have more than 1 stroke; 2 is very common. 25% of lightning flashes have about 4 strokes. Subsequent strokes usually have lesser magnitudes than the first stroke, but the rate of rise of the current is higher. With the subsequent strokes, whole lightning flash may last nearly one second [7].

In order to rate the switchgear and insulators employed in high voltage and medium voltage systems and to carry out their surge handling capability type tests, lightning current waveforms are artificially being created in the laboratories. Commonly used lightning current waveform to rate the surge current capabilities of equipment is the 10 kA, 8/20 μs waveform.

Depending on the impedance of the path that the wave travels, the created voltage waveform differs. However, the surge voltage appearing along a conductor has the same shape as the current waveform. This is due to the characteristic impedance of the line, which is a real value.

Characteristic impedance $Z = \sqrt{L/C}$ ***----- (4.1)***

Where, L = *Inductance of the line per unit length*
C = *Capacitance of the line per unit length*

In realistic measurements, characteristic impedance value is further simplified as [7];

Characteristic impedance $Z = 60\ \ln(2h/r)$ ***----- (4.2)***

Where, h = *Average conductor height*
r = *Conductor radius*

Typically characteristic impedance value is 450 Ω for MV overhead lines [9].

Mostly used voltage waveform is having 1.2/50 μs shape. Basic Impulse insulation Level (BIL) of high voltage and medium voltage equipment is defined as the peak value of a 1.2/50 μs voltage waveform that the equipment can handle, without damage.

Switchgear and equipment manufacturers use different waveforms with different magnitudes for specifying certain characteristics. Few examples are, 10 kA : 8/20 μs, 20 kA : 8/20 μs, 10 kA : 8/250 μs (slow decaying), 10 kA: 1/20 μs (steep) and 500 A: 30/60 μs (switching impulse).

In real case, lightning current magnitudes can be higher as 200 kA. However, being a tropical country where lightning is common during the monsoon season, Sri Lanka is getting lesser magnitude lightning surges, but with a higher occurrence rate. CEB takes 10 kA, 8/20 μs waveform for specifying the lightning current capability of the switchgear connected to the MV system and BIL as 170 kV for defining the impulse voltage capability.

4.1 Lightning effect on conductors

4.1.1 Direct and induced lightning

As discussed in the section 2.0, there is a number of possible ways that lightning surges can appear in power distribution network. There could be direct lightning strikes on the MV line or on the LV lines or on the service supply line. Nearby lightning strikes happening on the ground also can create induced surges due to electromagnetic and ground coupling with the conductors. Also cloud to cloud lightning can induce high magnitude surges on the distribution lines due to capacitive and inductive coupling. Further, surges attracted such way on the MV lines, LV lines and overhead earth wire can induce on each adjacent conductor when it travels through the line towards the ground path.

Figure 4.2 illustrates the typical phenomenon of a surge transfer along the MV line, before flashover. CEB's practice is to lay the overhead earth wire under the MV lines. Hence, direct lightning gets attracted directly to the MV line, as it is the top most circuit [8]. The figure shows a single MV conductor for easy understanding. Surge current 'sees' the MV line as an infinitely long conductor. Due to the very short duration of the surge (lasting about 100 micro seconds) and the very high rate of rise of the surge current waveform, it finds the MV line as an infinitely long loss less conductor, hence the characteristic impedance of the MV line comes into effect.

Characteristic impedance ACSR (Aluminium Conductor Steel Reinforced) is about 450 Ω [9]. As the characteristic impedance of the conductor is equal to the either directions, the surge current of the magnitude of 20 kA splits into two equal portions (10 kA each) and travels along either directions.

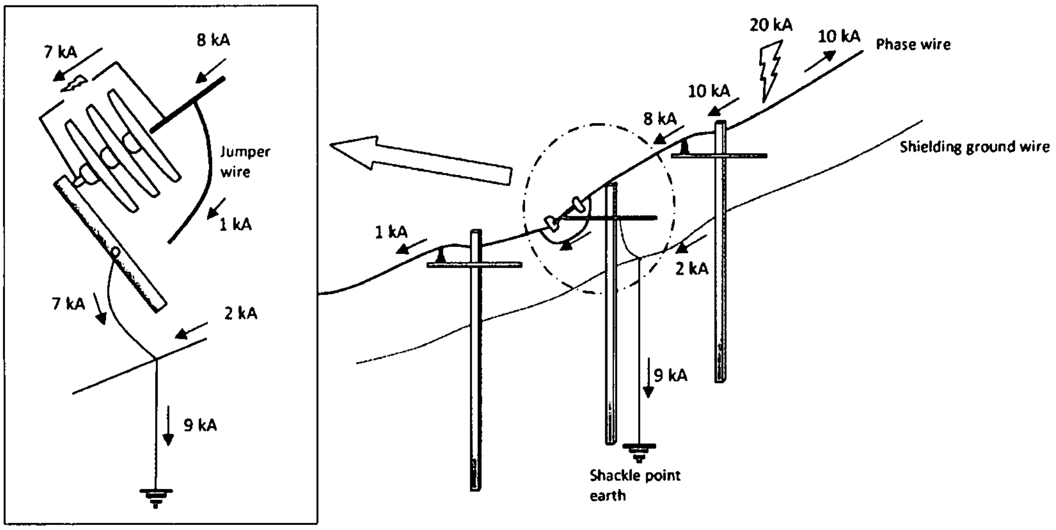


Figure 4.2 : Illustration of surge travelling along MV conductor and flashover

This current travelling along the MV line gets reduced due to the electromagnetic coupling with the shielding ground wire. In the example, the magnitude of the surge drops to 8 kA after a while and the balance 2 kA is induced on the overhead earth wire due to electromagnetic coupling. Also the steepness of the surge current gets reduced while it travels along the line. Near the shackle insulators due to the voltage pile up, flash over occurs (surge voltage exceeds the line insulation level) to the steel cross arm, which is connected to the ground wire, and then it gets dispersed into the earth. Line insulation level of our MV network is around 500 kV (concrete pole lines with earthed cross arms). After flashing over, about 1 kA current would have travelled along the conductor. This 1 kA current travelling along the conductor experiences a 'chopped wave' that has a chopped peak and very high decreasing rate because of insulator flashover. It is proven that equal magnitude currents flow along either directions of the MV conductors, after flashing over.

Corona effect has an impact on the travelling surges and changes the surge impedance. Very high voltages created on the conductors breaks down the air medium surrounding the conductor, creating a corona envelope, increasing the capacitance, thus decreasing the surge impedance. As the corona effect supports capacitive coupling with other conductors, slope of the wave front decreases while it travels along the line. Most of the time flash over occurs before considerable corona is developed [7]. Because of this reason, the effect of corona can be neglected. In addition to corona, small partial discharges also occur before an insulator flashes over.

Unlike in direct surges, it has been found that induced voltages on lines are of magnitudes less than 300 kV. As to avoid nuisance tripping due to flashover caused by induced over voltages, it has to be ensured that the line's insulation level is higher than this value [7].

Rusck's simplified equation gives the peak voltage induced by nearby lightning.

Peak induced voltage $\quad U_p = 36.5\ (I\,h/y) \quad$ ***----- (4.3)***

Where, *I = peak lightning current in kA*
h = height of the line from ground
y = distance of the stroke, away from the line

If a lightning of the magnitude 20 kA occurs at 100 m away from the line, the Rusk's equation gives the magnitude of the induced voltage as 73 kV (assuming the line height is 10 m).

As this equation is developed for ungrounded circuits, it will be very useful for estimating the induced overvoltage magnitudes in CEB's applications (33 kV network is indirectly grounded, so that this equation applies).

4.1.2 Behaviour of the travelling lightning wave

When a lightning wave travels along a line and meets the transformer's MV connection, it sees the transformer as a very high impedance due to the high rising rate of the current. This is now seen as an open connection by the travelling wave and gets reflected. Doubling of the voltage and the steepness of the wave occurs at this point. This voltage with double magnitude and rising rate travels back to the arrester and reflects negatively. This process happens until the voltage near the arrester builds up for discharging the surge current. Because of this voltage buildup due to reflection, the voltage at the transformer terminal would be higher than the voltage at the arrester terminal, at the time of the arrester discharging the surge current. Voltage at the arrester top terminal would be approximately its residual voltage value at this moment. Due to this reflection phenomenon, we understand that having an arrester on the MV conductor only maintains the voltage at the arrester terminal near its residual voltage, but creates higher voltages on either directions of the line [9]. Connecting arresters at a considerable distance from the transformer is therefore detrimental to the transformer. It is very important to select arresters with low residual voltage ratings and employing them as much as closer to the equipment to be protected (transformers).

4.1.3 Protective distance

As discussed in the section 4.1.2., the distance of the arrester from the transformer has to be shortest possible to ensure maximum protection of the transformer.

The voltage at the transformer terminal is given by,

$$U_t = U_{res} + (2S\,l\,/\,v) \qquad \text{-----}\ (4.4)$$

where, U_t = *Voltage at the transformer terminal (kV)*

U_{res} = *Residual voltage of the arrester (kV)*

S = *Slope of the waveform near the arrester*

l = *Length between arrester terminal and t/f (m)*

v =*Speed of the wave propagation (m/s)*

The slope of the lightning wave decreases as it travels. This is given in the equation below.

The slope 'S' near the arrester is given by

$$S = \frac{1}{\left(\frac{1}{S_0} + k\,d\right)} \qquad \text{-----}\ (4.5)$$

Where, S_0 = *Slope of the waveform at a distance 'd' along the conductor*

d = *Distance from the original lightning strike, to the arrester*

k = *5×10^{-6} µs/kVm*

'k' depends on the geometry of the overhead line. When substituting in equation (4.4), the distance '*l*' is taken as a+b (see figure 4.3). Speed of the wave '*v*' is very close to the speed of light, which is 300 m/μs. Keeping the length '*b*' as minimum (almost zero) and length '*a*' less than 4m is recommended to ensure minimum protection of the transformer [6]. With the advent of transformers with arrester mounting bracket fixed to the tank, the protective distance is automatically maintained around 0.5 m.

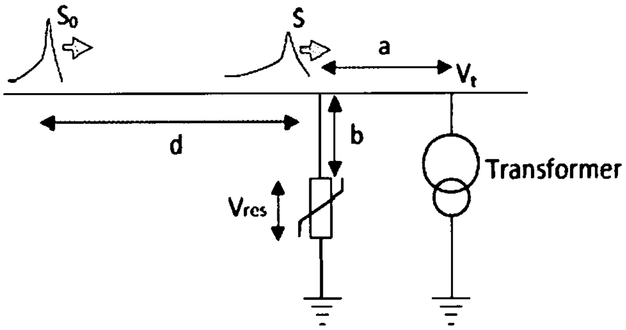


Figure 4.3 : Illustration of protective distance

4.2 Lightning in Sri Lanka

Various countries in the world have various types of lightning patterns depending on their climatic conditions. As discussed earlier, the magnitude of lightning surges can be in the order of 200 kA and with very high gradients. It is the belief of lightning experts, that Sri Lanka being a country that experiences rain during the most of the year, is blessed with lightning strokes with lesser energy, but with high occurrence rate. It is our experience that the beginning of the monsoon season is having intermittent lightning with high energy and the strength and occurrence rate of lightning diminishes once the rain starts.

Following empirical formulas are established based on the statistical evidence, to determine the lightning occurrence rates [7].

$$N = 2.8\, N_g\, h^{0.6} \qquad \text{-----}\ (4.6)$$

$$N_g = 0.04\, T\, d^{1.25} \qquad \text{-----}\ (4.7)$$

Where, N = *Number of flashes on conductor, per 100 km length per year*
N_g = *Ground flash density (flashes per km^2 per year)*
h = *Conductor height (in metres)*
T_d = *Thunder days per year*

To determine the thunder days per year in a particular zone of the country, the isokeraunic map developed in 1968 and updated with experience has become the only available guideline [10]. Lightning is very common in the western and central part of the country. As shown in the figure 4.4, isokeraunic map of Sri Lanka, we can determine the average thunder days as 80 in most of the critical zones of the country.

By substituting in equation (4.7), we get the ground flash density roughly as 10 flashes per km^2. By substituting this value in equation (6) with conductor height taken as 10 m, we get N = 111. Hence, the number of flashes occurring during a year on 100 km conductor length of the network would be 111. This is fairly a high value. It is seen that occurrence rate in central Europe comes around 8 strokes per 100 km per year, but in the areas with high thunderstorm activity, this has gone upto 100 strokes per km per year [9].

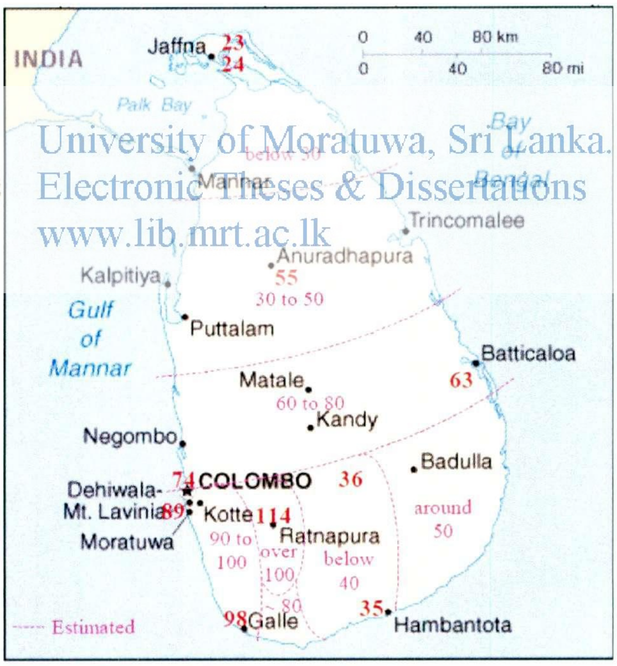


Figure 4.4 : Isokeraunic map of Sri Lanka [10]
(Original is in colour)

It is found that 95% of the lightning has magnitudes of 14 kA [9]. As proposed through the studies done in USA and Europe, based on 50% probability, most likely lightning current occurring on MV circuits is having 35 kA peak, with 5.5/75 μs nature [7].

Voltage peak created by above lightning current incident on the conductor is calculated as,

$V \quad = 450\Omega \times 35\ kA = 15{,}750\ kV$

The rate of rise of the voltage waveform is (initial slope S_0),

$S_0 \quad = Z.\ di/dt \quad = 450 \times (35/5.5) \quad = 2{,}864\ kV/\mu s$

Assuming the lightning occurs at a 100 m distance on the line, by substituting in equation (4.5), we get the voltage slope near the transformer as,

$S \quad = 1{,}178\ kV/\mu s$

If the transformer BIL is 170 kV, the protective level near the transformer is defined as 170/1.45 = 117.6 for 36 kV nominal MV systems [11]. Assuming the residual voltage of the arrester to be 100 kV and by substituting in equation (4.4), we get the protective distance '*l*' as

$l \quad = 2.24\ m$

(l is the conductor length between arrester terminal and transformer HV terminal)

Table 4.1 shows the voltage magnitude, calculated in the same manner. Initial slope and slope after travelling 100 metres for different induced lightning voltage waveforms incident on a MV line, assuming a line characteristic impedance of 450 Ω and arrester residual voltage of 100 kV.

Incident Lightning Waveform	Voltage magnitude (kV)	Initial voltage slope ($kV/\mu s$)	Slope after 100 m ($kV/\mu s$)	Modified rise time of the attenuated voltage waveform (μs)	Protective distance (m)
35 kA, 5.5/75 μs	15,750	2,864	1,178	13	2.24
20 kA, 1.2/50 μs	9,000	7,500	1,579	5.7	1.67
10 kA, 1.2/20 μs	4,500	3,750	1,304	3.5	2.02
10 kA, 8/20 μs	4,500	563	439	10	6.01

Table 4.1 : Initial and final slopes of lightning voltage surge waveforms and their protective distances in MV circuits

It is accepted that there is high probability of having 20 kA magnitude lightning in Sri Lanka [10]. In worst case, initial rise time of these surges would be in the order of 1.2 μs. If directly hit on a line, this waveform can generate a very high voltage such as 9,000 kV (table 4.1). Very high magnitude voltages induced on MV lines tend to flashover across insulators at first junction because line insulation level is around 500 kV [7] to 660 kV [9] in concrete pole structures (with earthed cross arms). Hence, transients having very high magnitudes may end up with chopped waves, in which their voltage drop creates another transient with a lesser slope. Also corona and electromagnetic coupling effects reduce the magnitude and slope further.

When a lightning hits on a MV line, the surge current initially divides into two equal portions and travel in both directions of the line. Taking into account the most probabilistic approach, It can be hence justified the use of 10 kA, 8/20 μs current waveform for characterizing lightning current in CEB's MV network. All other surges would be indirectly induced ones having lesser magnitudes. In most cases it is expected that the lightning current gets shared among the three phase conductors when it hits on MV line. This can happen because we use horizontal cross arms with the conductors running on a horizontal plane. Taking into consideration this aspect, the most probable lightning current experienced on the conductors would have magnitudes in the range of 3 kA to 5 kA.

4.3 Lightning effects on transformers

4.3.1 Lead length and lead voltage

When a current having a very high rate of rise flows through a conductor, a very high voltage is generated due to the inductance of the conductor. The voltage created by the resistive component of the conductor is negligible when compared with the voltage induced due to inductance. Likewise, when an arrester discharges the lightning current into the ground, a very high voltage is induced on the conductor. This voltage applies across the HV terminal and the tank of the transformer, added with the residual voltage of the arrester. Voltage applied to the transformer insulation is dependent on the length of the lead involved, which is called the 'lead length'. Figure 4.5 shows a transformer installation made to the method 'B' of the figure 3.3. The voltage created by the lead length is V_{L1} and the arrester residual voltage during current discharge is V_{res}. Total voltage applied across the insulation is $V_{L1}+V_{res}$. If 10 kA, 8/20 μs current is flowing through the copper arrester earth conductor, taking resistance of copper as 0.336 mΩ/m and inductance as 1μH/m we can calculate the lead voltage V_L as follows. It is assumed that lead length is 1 m.

$$V_L = L\frac{di}{dt} + IR$$

$$= (1 \times 10/8) + (10 \times 0.336) = 1250 + 3.36 = 1253.36\text{ V}$$
$$\approx 1.3\text{ kV}$$

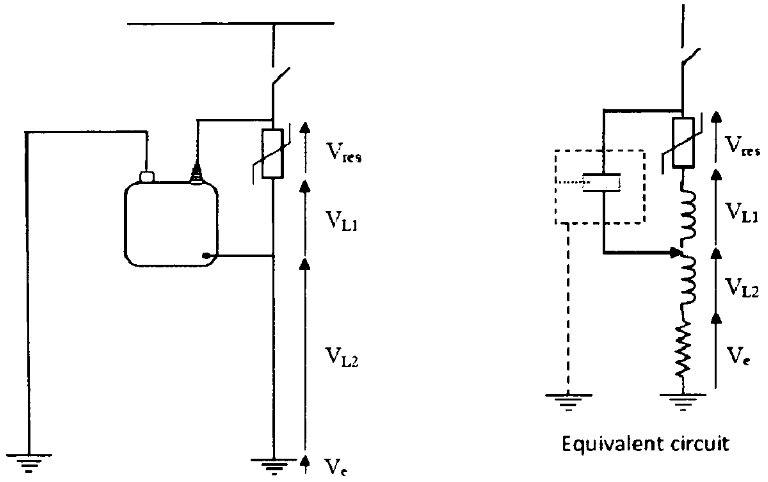


Figure 4.5 : Voltage distribution on the HV earth lead when arrester functions

The voltage across the insulation is $V_L + V_{res}$. If the residual voltage of the arrester is 100 kV, total stress on the insulation would be 101.3 kV. We can see that the highest voltage contribution is by the arrester's residual voltage.

Practically the earth lead is seldom straight but bended at several places. Bends, joints and punctures on the copper earth lead introduce higher inductances than expected. Hence in real case the lead inductance can become double than expected. Longer leads naturally have bended profiles. It can be shown that in the method 'C' of figure 3.3, the lead voltage only becomes approximately 10 kV when the possible bends are also taken into account. Hence it is always safer to have lower lead lengths as shown in the figure 4.5.

When considered CEB's transformer installation practices (figure 3.3), less lead lengths are achieved in the methods 'A' and 'B'. If the HV connection is made first on the transformer's HV terminal and then on the arrester, again the lead length increases. This is not now practiced in CEB installations.

4.3.2 Tank potential rise

Transformer tank potential rise depends on the addition of the voltages induced on the lead that connects the tank upto the earth connection and on the voltage rise at the earth rod (in the figure 4.5, $V_{L2}+V_e$). Having a higher potential on the tank during the lightning surge that lasts few micro seconds would be advantageous to maintain low stress on the transformer insulation, as the potential difference across the insulation becomes low. When lead length is minimized, connecting length of the tank and the earth gets increased. In other words, minimizing the 'lead length' causes tank potential to rise.

Voltage rise due to earth impedance (V_e in figure 4.5) can have an impact on the voltage applied to the insulation. This is difficult to explain as both the tank potential and the HV terminal voltage is influenced by this. Reasons for the increase of V_e may be due to poor earth lead to rod connection, poor earth DC resistance, poor earthing profile, etc.

Some argue that the tank potential rise can lead to LV insulation failure as it can encourage core to LV winding spark over. As the transformer's tank is solidly connected to its core and the LV winding (with earthed star point) is wound very close to the core, there is a possibility of such flash over. As the LV winding also gets a considerable amount of the surge voltage induced through stray capacitances [12], this matter has to be looked in a more analytical manner.

Chapter 5

Transient wave simulation

5.0 PSCAD software tool for transient analysis

It is always not possible to determine the transient response of transformers for lightning surges using simple calculations. The best way to visualize this would be through a real simulation done in a laboratory. For such an analysis there exist many practical constraints. Alternative option for this would be carrying out a model simulation with the aid of software. PSCAD software (version 4.2.1 Eval – August 2006) developed by the Manitoba HVDC research centre is used for modeling different lead connection practices of transformers to observe the variation of voltages at different nodes, under various lightning surges.

Several researches have been done for modeling transformers for transient analysis. Most of the models developed are for analyzing the secondary voltage responses under small scale transients. This is demanded by the mass scale manufacturing industries because critical voltages appearing at the secondary are of great concern for the machinery having sophisticated electronics. As our intention is to observe the impacts to the transformer insulation against various lead connection practices, a basic transient model for transformers and MV, LV lines is developed with few modifications done to the steep front analysis tool provided with PSCAD software.

5.1 Basic installation arrangements

Transient analysis is done for few selected arrangements as shown in the figure 5.1. Arrangement 1 is a new installation method proposed by the author, which is not practiced in CEB yet. In this method, the flexible leads of the three arresters are directly connected to the transformer tank at the top and a special connector will be required to connect the three arrester bottom terminals to the earth lead. Arrangement 4 which is very similar to the arrangement 1, is being practiced in few areas in CEB.

Here also the flexible leads of the arresters connect to the transformer tank first. Then the earth lead connects to the tank's earth flange, separately.

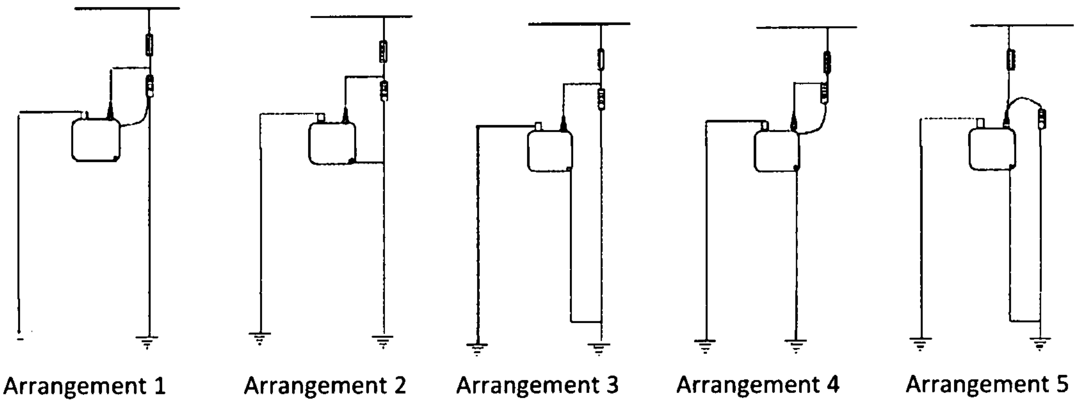


Figure 5.1 : Transformer installation arrangements used for transient analysis

Compared with arrangement 1, arrangement 4 has its advantages in installation as it uses only the available connectors and flanges. However, it is observed that the mild steel transformer tank also becomes a part of the surge current path that contributes to lead length.

Arrangement 2 is the newly proposed method that is being practiced since 2009 presently in Western Province South II of CEB, but not widely adopted yet. In this method, the transformer tank connects to the arresters' ground lead with a 'T' formation, using a compression clamp. This was introduced before the transformers came with the arrester mounting bracket fixed to the tank, hence arresters had to be fixed on a separate cross arm. This method still can be used with the modern transformers with arresters mounted on the tank.

Arrangement 3 is the most common installation method presently followed. This method has the highest lead length. In this method, the tank and arrester earth leads run separately along the pole and connect to the same earthing system.

Arrangement 5 is not practiced in general, but can rarely be seen in certain places. Here, the MV connection is first made to the HV terminal of the transformer, not to the arresters' top terminal. This is having even more lead length than that in the arrangement 3, because arrester connecting lead also adds to the lead length.

5.2 Parameter selection for modeling

5.2.1 MV line parameters

MV line is modeled using the Bergeron model provided in PSCAD. A line length of 100 m is considered for the analysis. Embedded values used for positive sequence travel time of the wave is adjusted to 3×10^{-9} s/m and positive sequence surge impedance to 450 Ω. Positive sequence resistance is taken as 0.01 Ω/m, same as suggested in the model.

5.2.2 Surge Signal generation

For the lightning signal, following formula is used.

Lightning current $I = -Ae^{Bt} + Ce^{Dt}$ ***----- (5.1)***

Where 'A' and 'C' are constants influencing the magnitude of the waveform, 'B' and 'D' are negative constants representing the time constants of the two saturation curves that constitute the lightning current waveform.

The lightning current waveforms are characterized by their magnitude, rise time and time taken to reach half of the peak. Since the values of time constants of the waves are unknown, the waveforms were simulated with the aid of a spread sheet by giving arbitrary values for A,B,C and D to get the required waveforms through curve fitting.

Waveform $I = -Ae^{Bt} + Ce^{Dt}$	A	B	C	D
5 kA, 8/20 μs	34	-166,660	34	-111,500
10 kA, 8/20 μs	69	-166,660	69	-112,000
20 kA, 8/20 μs	70	-200,000	70	-90,000
10 kA, 1.2/50 μs	10	-4,877,000	10	-14,260
4 kA, 30/100 μs	7	-70,000	7	-12,200

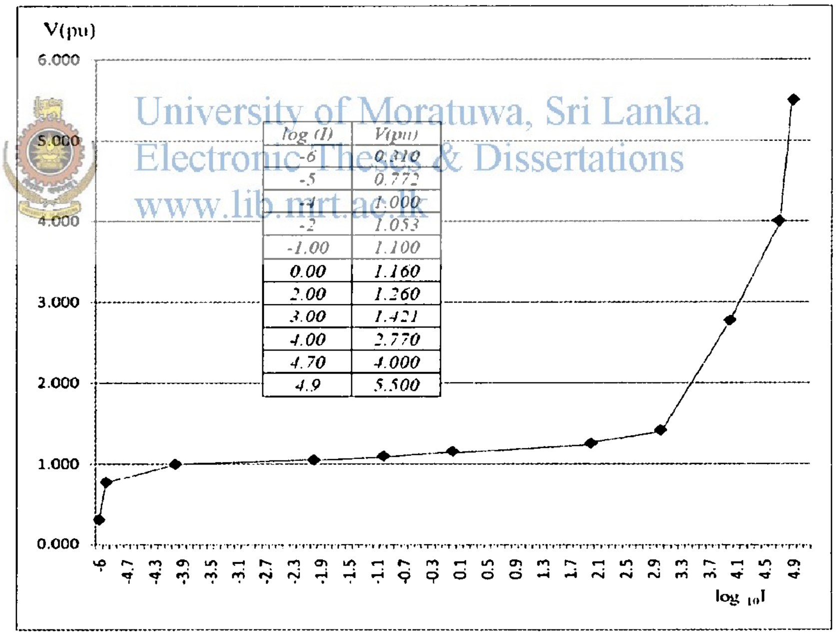
Table 5.1 : Constants of the surge waveforms found through curve fitting

5.2.3 Selecting lightning arrester parameters

In selecting lightning arrester parameters, figures are taken to satisfy CEB specifications.

Possible maximum system (line) voltage		U_S	=	36 kV
Possible maximum per phase operating voltage	$36/\sqrt{3}$		=	21 kV
Maximum continuous operating voltage (MCOV)	21 x 1.4 *	U_C	=	29 kV
Rated voltage	29 x 1.25 ψ	U_R	≈	36 kV
Rated discharge current		I_R	=	10 kA
Residual voltage at the rated discharge current	U_R x 2.7 **		≈	100 kV

In modelling the lightning arrester, reference is made to IEEE protocol [17]. A remarkable feature of this protocol is the two arresters connected in parallel. This is to give the effect of a higher overvoltage for fast front transients.



log (I)	*V(pu)*
-6	*0.310*
-5	*0.772*
-4	*1.000*
-2	*1.053*
-1.00	*1.100*
0.00	*1.160*
2.00	*1.260*
3.00	*1.421*
4.00	*2.770*
4.70	*4.000*
4.9	*5.500*

Figure 5.2 : Arrester data used for simulation
(Original is in colour)

* *Multiplied by 1.4 to compensate for temporary overvoltage at line to ground faults[7]*

ψ *According to [15], for MV systems of 36 kV range voltages,* $U_R = 1.25\ U_c$

** *Discharge factor = Residual voltage of the arrester / Rated voltage of the arrester taken as 2.7 [14]*

For medium frequency ranges, V-I characteristics is shown in figure 5.2. To represent the time delay caused by ZnO material, a tuned circuit of an inductor and a resister is connected.

5.2.4 Inductance and stray capacitances

Inductance of connections is taken as 0.48 μH [26]. An inductance of 1 μH is assumed for DDLO switch. All other inductances used to represent the connecting leads are done with reasonable assumptions as to represent their lengths and bends involved in the different installation arrangements. In addition to the use of stray capacitances in the order of 2nF [26], a reasonable assumption is made to determine the combined capacitance to ground, based on experimental test values. Figure 5.3 shows results obtained for combined impedance to ground versus frequency curve of a 115/23 kV, 50 MVA transformer.

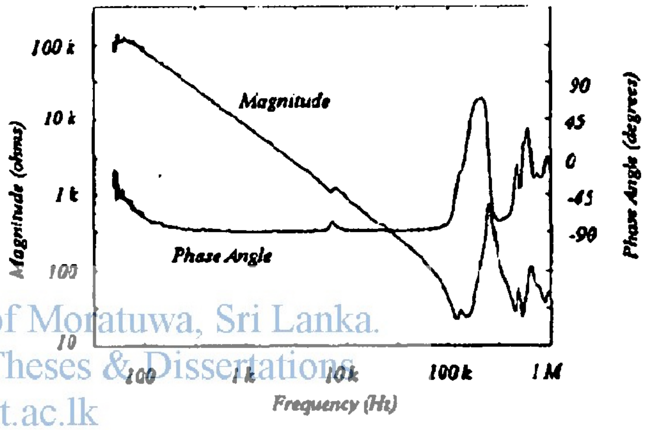


Figure 5.3 : Stray impedance of a 115/23 kV, 50 MVA transformer [18]

It can be seen that upto around 100 kHz frequency, the impedance is almost constant. It is believed that the variations beyond this frequency are due to measurement inaccuracies [18]. If assumed a surge current waveform with 8μs rise time, it is in analogy with a wave form with a steady state frequency of 125 kHz (= 1/8 μs). Hence, impedance measurement around 100 kHz in the graph of figure 5.3 can be used for determining the leakage capacitive reactance of the transformer. We can represent the combined leakage capacitive reactance of the transformer as 40 Ω.

Hence, $1/(2\pi f C) = 40$

We get, $C = 1/(2\pi \times 125\times10^3 \times 40) = 31.8\ \text{nF}$

After rounding off, the combined capacitance to ground is taken as 32 nF in the PSCAD simulation model.

5.2.5 LV distribution and earthing

For simplicity, it is assumed that the LV distribution is done with bundled cables. Hence, in the high frequency transient model LV phases and neutral are shown combined due to strong coupling. For LV, a 10 m distribution cable length with very high ground impedance (10^6 Ω) is modeled. Earth resistance is taken as 30 Ω, which is a better practical figure (see table 3.1). Length of the earthing conductor is assumed to be 5 m which corresponds to the average length in practical installations in most of the cases, except where the reasons for deviations are mentioned.

5.2.6 Other assumptions

It is assumed that the inductance of copper conductors is 1 μH/m. This assumption is approximately valid for most of the copper conductor sizes used [19]. When it comes to arrangements 4 and 5 (figure 5.1), the transformer tank also functions as a conductor. It is assumed that the transformer tank is equivalent to a length of one metre mild steel conductor. Mild steel is having an inductance ten times that of copper, hence it is assumed that the inductance involved with the transformer tank is 10 μH.

5.3 PSCAD Simulation

5.3.1 Installation arrangement 1

Figure 5.4 shows the installation arrangement 1, modeled in PSCAD. The length of the cable connecting the arrester's bottom terminal to earth is taken as 5 m, hence an inductance of 15 μH is attributed, considering the possible bends also. The length of the cable connecting tank to the arrester bottom connection is about 1 m in length, hence taken as 1μH as it is a short length of cable without bends.

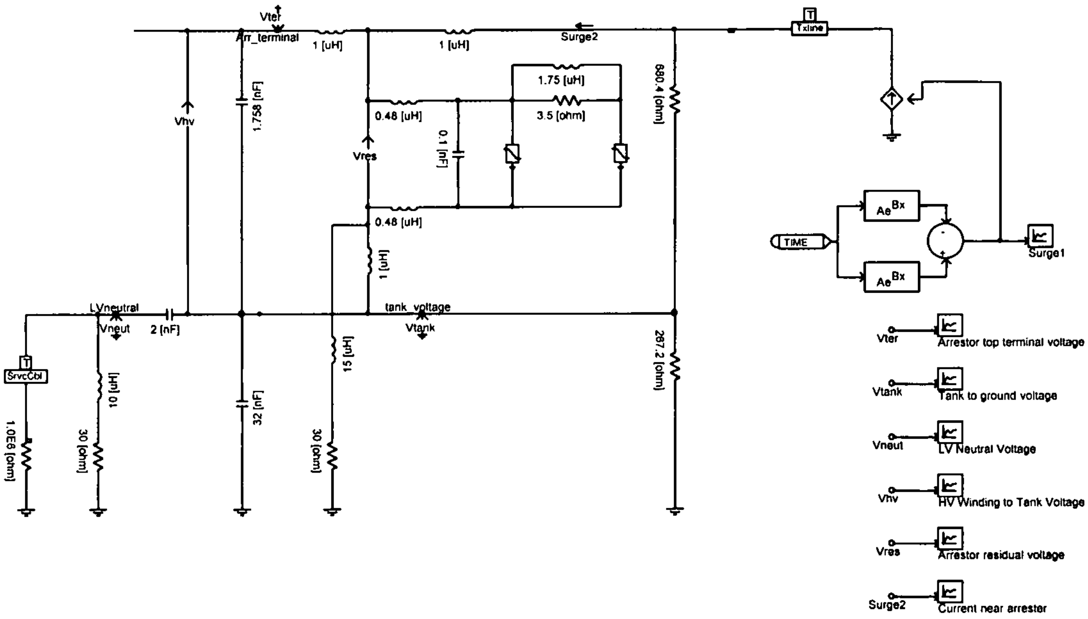


Figure 5.4 – Installation arrangement 1 modeled in PSCAD

5.3.2 Installation arrangement 2

Figure 5.5 shows the installation arrangement 2, as modeled in PSCAD. Here the length of the cable connecting the arrester's bottom terminal upto the 'T' joint is taken as 1 m and 2 µH is attributed for this length, evaluating the bends. The length of the cable connecting tank to the arrester earth lead is about 1 m in length, hence taken as 1µH as it is a straight part. Remaining lead that runs to the earth is taken as 4 m in length and 11 µH is given, considering the possible bends.

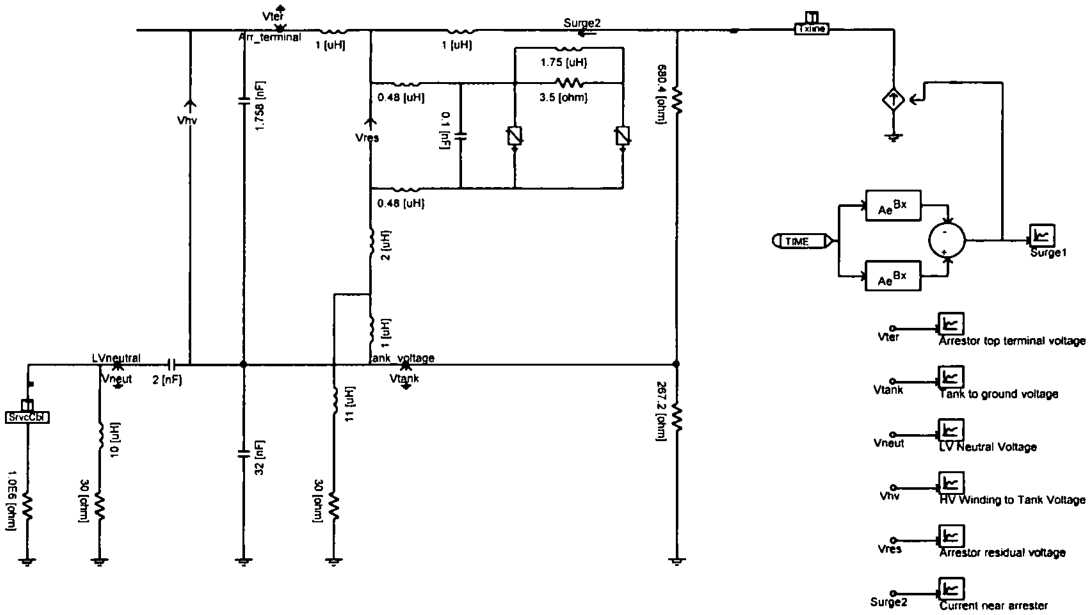


Figure 5.5 – Installation arrangement 2 modeled in PSCAD

5.3.3 Installation arrangement 3

Figure 5.6 shows the installation arrangement 3 as a PSCAD model. The length of the cable connecting the arrester's bottom terminal to the earth is taken as 5 m, hence 15 μH is given, considering the bends. The tank connection that runs to the earthing point is about 4 m in length, but is having bends. Hence, 13 μH is given for this, taking into account the inductance due to bends and the connecting inductance. Inductance of 1 μH is given for the earth rod.

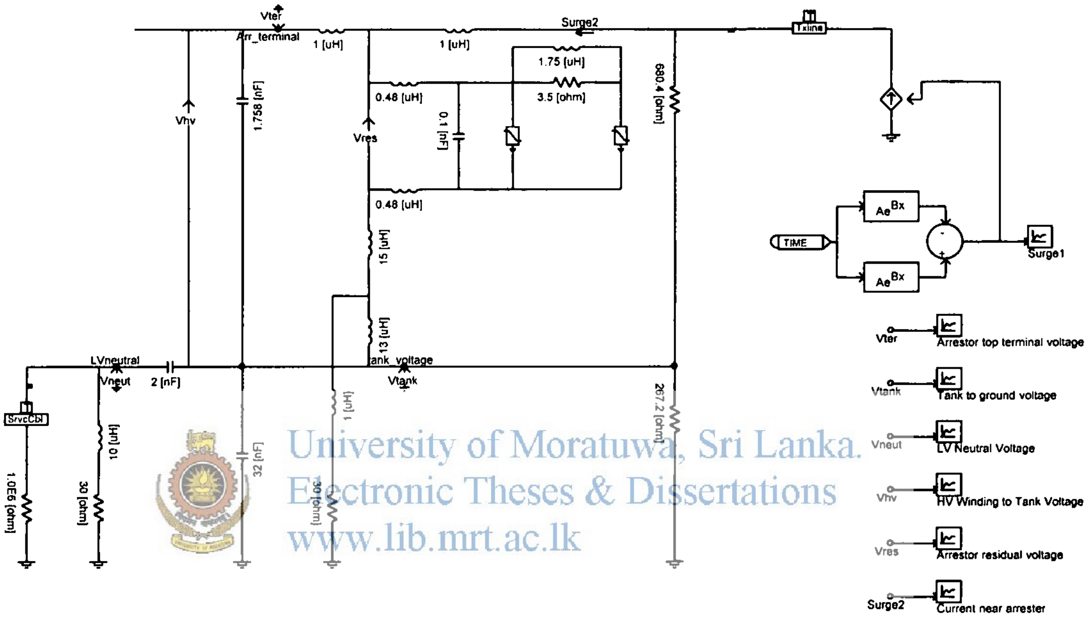


Figure 5.6 – Installation arrangement 3 modeled in PSCAD

5.3.4 Installation arrangement 4

Figure 5.7 shows the installation arrangement 4, modeled in PSCAD. The length of the arrester flexible leads is about 1 m, but considering the bend it takes, inductance is taken as 2 μH. Mild steel tank of the transformer comes into effect as a conductor to divert the surge current, in this arrangement. Considering the properties of mild steel and the connecting inductances, 12 μH is attributed for this. Length of the lead that connects the tank to the earth is about 3 m in this arrangement. 8 μH is attributed for this length.

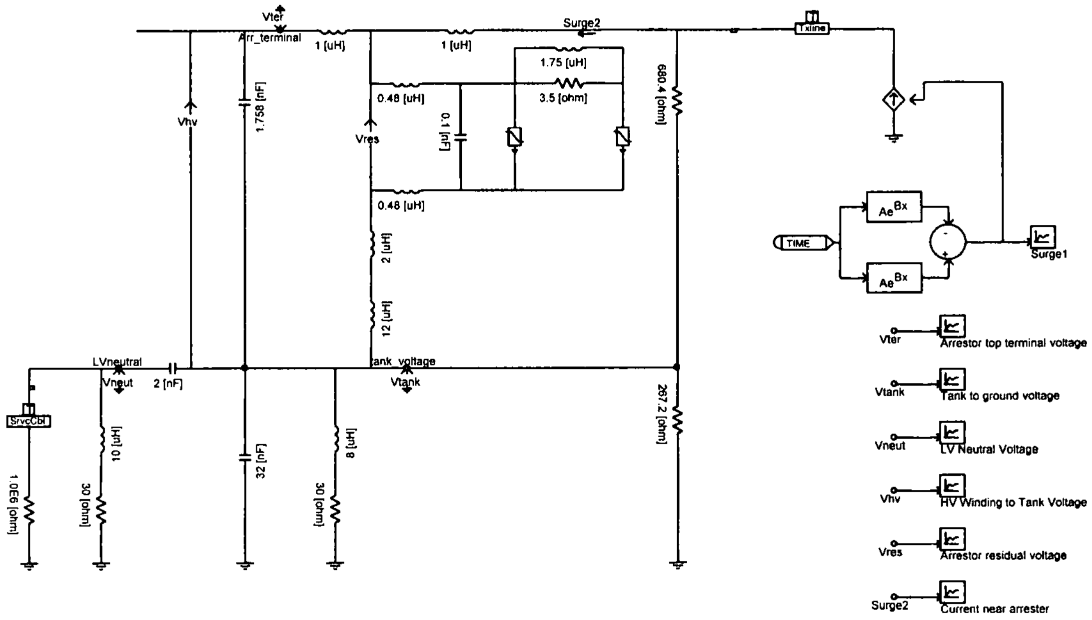


Figure 5.7 – Installation arrangement 4 modeled in PSCAD

5.3.5 Installation arrangement 5

This is almost similar to the arrangement 3, where separate leads are employed for the arrester earth and tank earth, but the difference is that the MV tap-off connection is first made to the HV terminal of the transformer and then to the arrester. Hence, a lead length of about 1 m comes into effect. Considering the bends and connections, 5 μH is attributed for this lead part. All other parameters remain same as in the arrangement 3. Figure 5.8 shows the installation arrangement 5, as modeled in PSCAD.

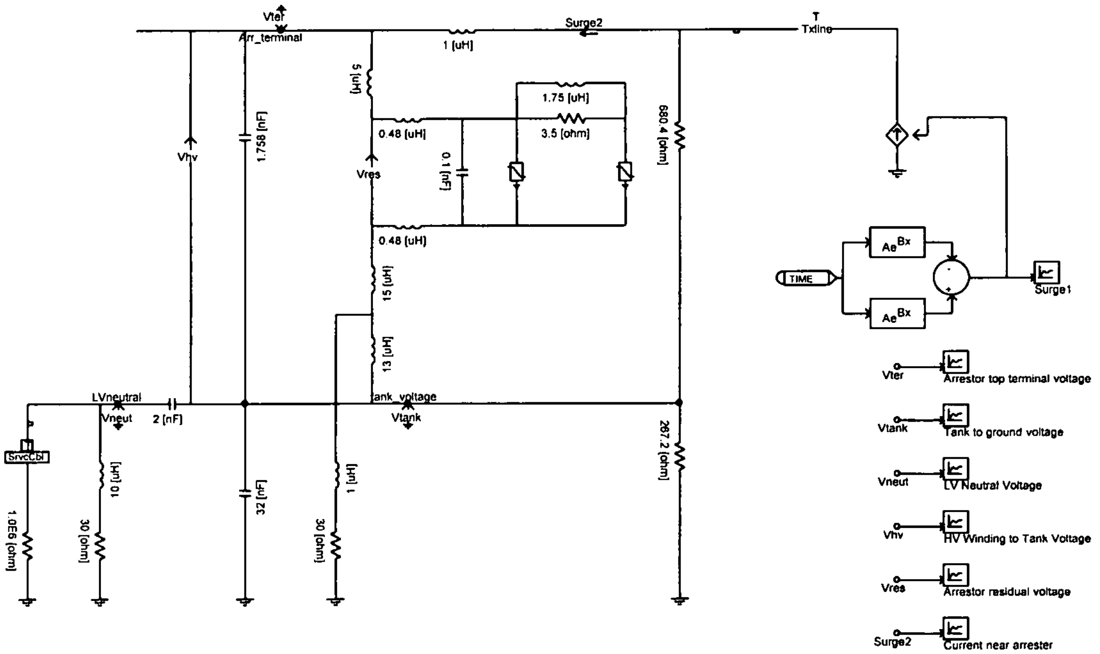
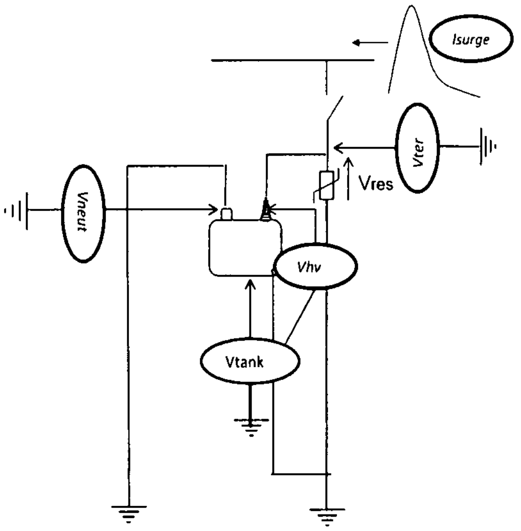


Figure 5.8 – Installation arrangement 5 modeled in PSCAD

5.3.6 Measurement quantities and nodes

Output measurements of voltages and currents are shown in figure 5.9.



I_{surge}	Surge current feeding the arrester
V_{ter}	Arrester top terminal voltage w.r.t. ground
V_{res}	Arrester residual voltage
V_{tank}	Transformer tank voltage w.r.t. ground
V_{hv}	HV terminal voltage with reference to tank
V_{neut}	LV neutral voltage with reference to ground

Figure 5.9 : Description of output measurement nodes

(Original is in colour)

5.3.7 Output settings

In the output graphs, sampling time and channel plot step durations are selected as 0.01 μs, whereas simulation run time is taken as 100 μs.

5.4 Simulation results

Output plots of the simulations done for 10 kA, 8/20 μs surge current waveform are shown in the figures 5.10 to 5.14. Further, sensitivity analysis is done for all the five waveforms given in the table 5.1. As we are interested only on the peak voltages, peak values are extracted from the output plots and are summarized in table 5.2.

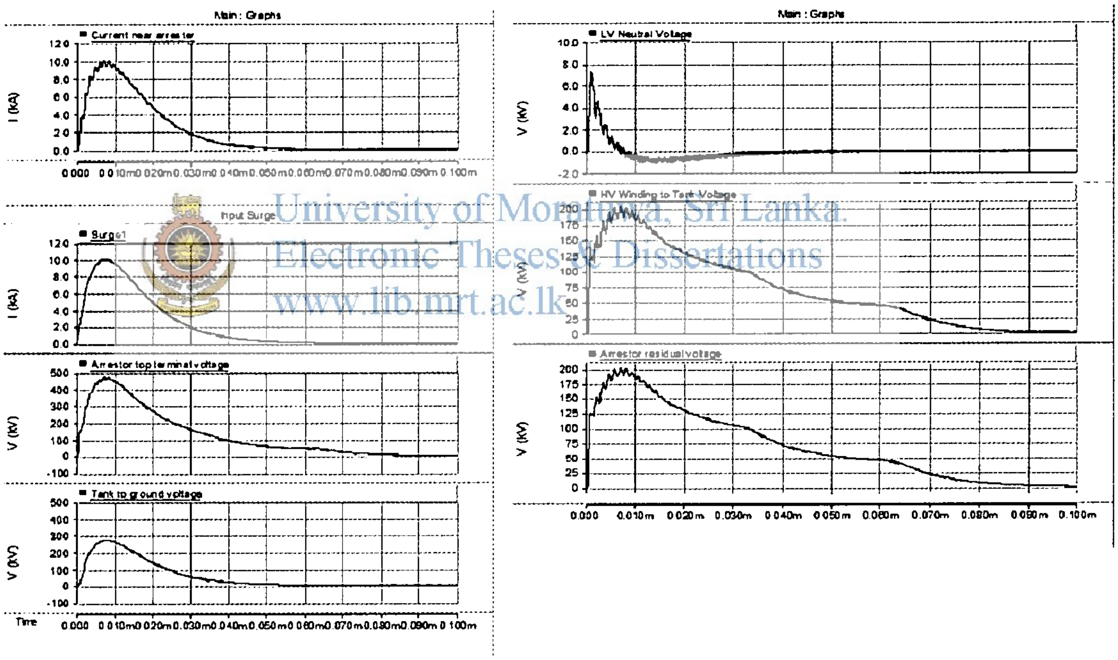


Figure 5.10 - Output plots for arrangement 1 with 10 kA, 8/20 μs waveform

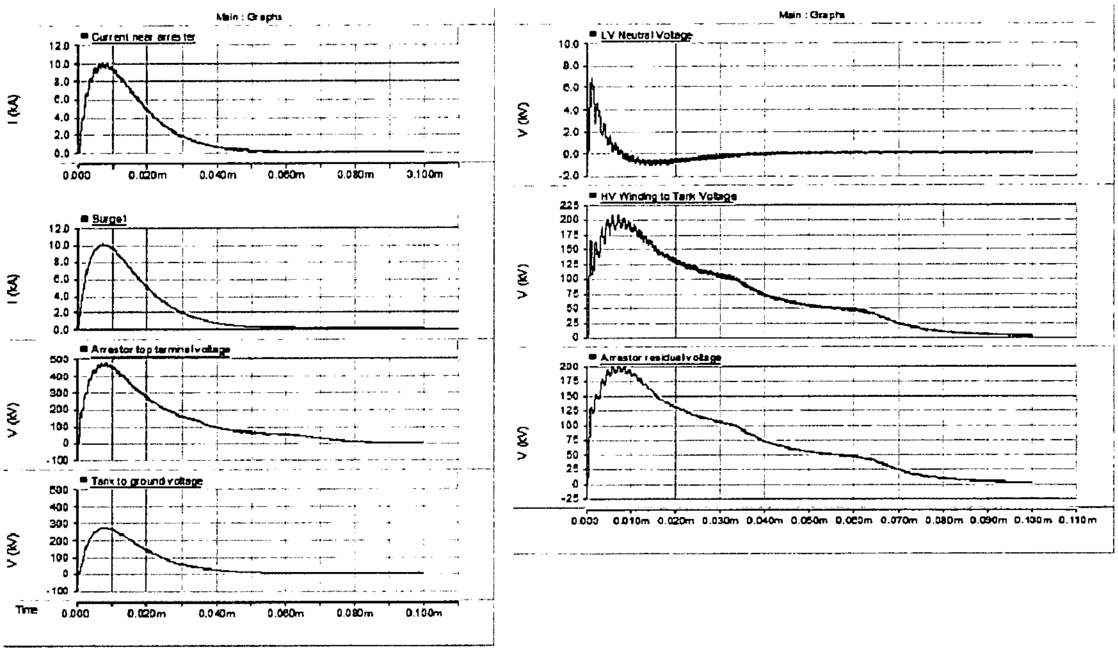


Figure 5.11 - Output plots for arrangement 2 with 10 kA, 8/20 µs waveform

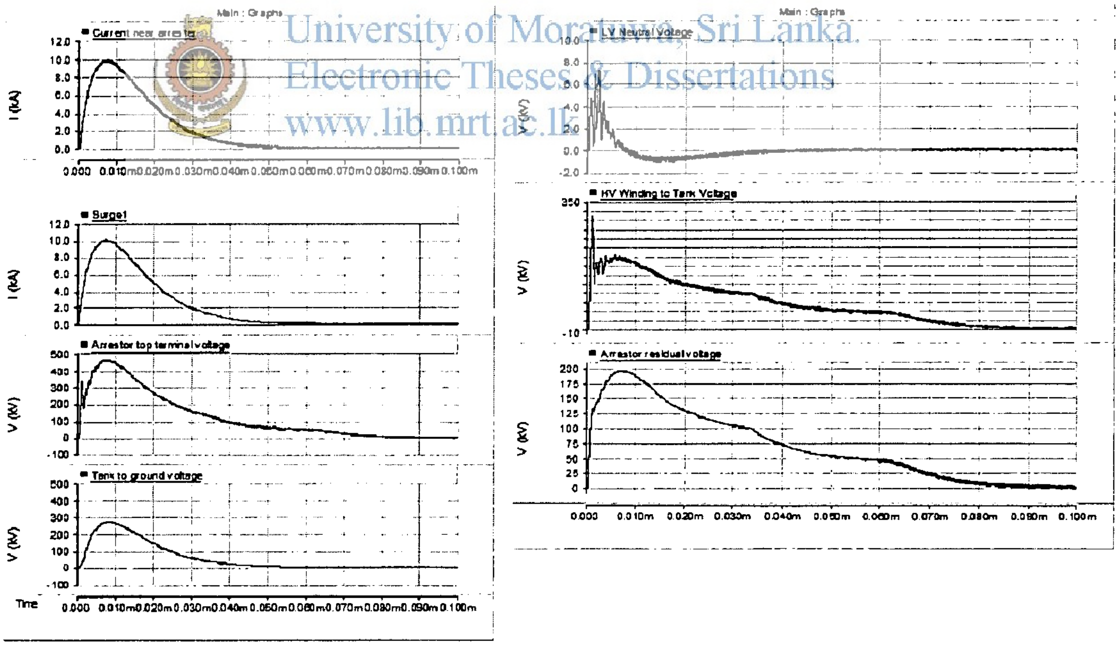


Figure 5.12 - Output plots for arrangement 3 with 10 kA, 8/20 µs waveform

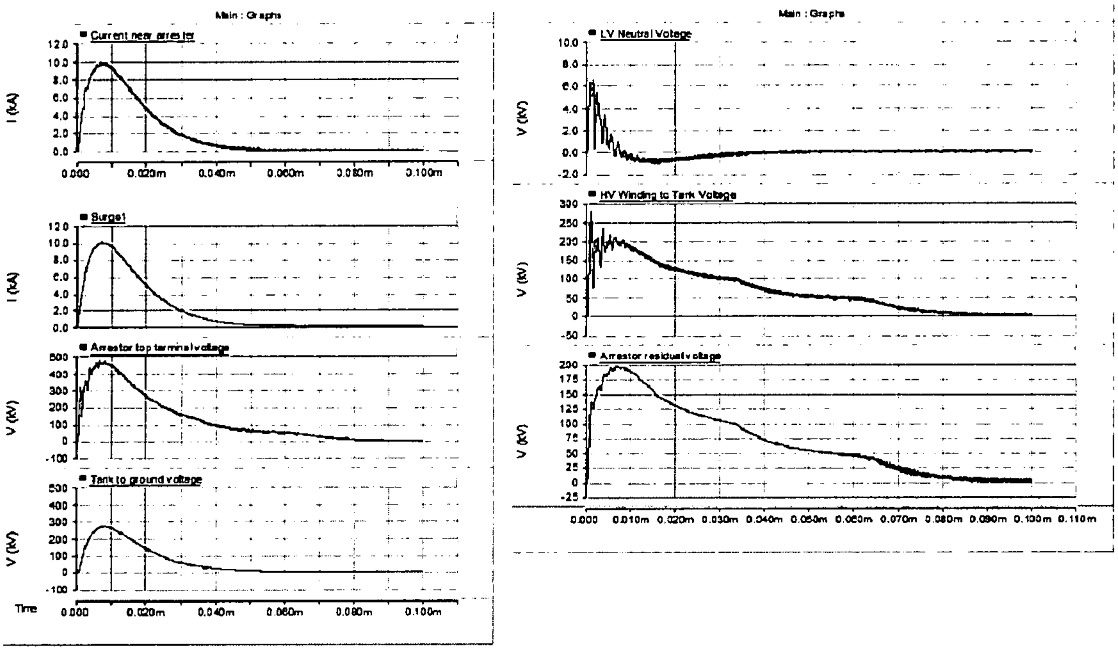


Figure 5.13 - Output plots for arrangement 4 with 10 kA, 8/20 μs waveform

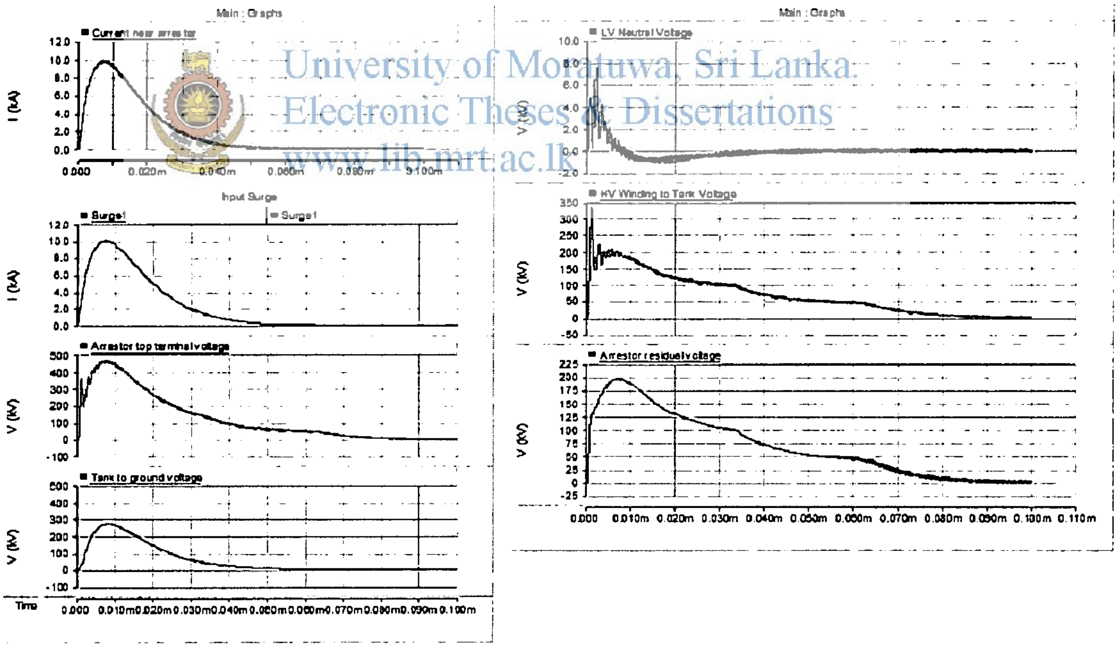


Figure 5.14 - Output plots for arrangement 5 with 10 kA, 8/20 μs waveform

Surge waveform		*Unit*	Simulation arrangement (as per figure 5.1)				
			1	2	3	4	5
5 kA, 8/20 µs	I_{surge}	*kA*	4.9	4.8	4.8	4.7	4.9
	V_{ter}	*kV*	269	269	267	270	267
	V_{res}	*kV*	133	133	131	132	131
	V_{tank}	*kV*	136	135	135	134	135
	V_{hv}	*kV*	135	136	182	169	193
	V_{neut}	*kV*	3.3	3.1	3.6	3.3	3.8
10 kA, 8/20 µs	I_{surge}	*kA*	9.8	9.9	9.9	9.8	9.9
	V_{ter}	*kV*	473	474	467	475	469
	V_{res}	*kV*	202	200	196	197	196
	V_{tank}	*kV*	273	271	271	270	270
	V_{hv}	*kV*	204	207	313	279	339
	V_{neut}	*kV*	7.2	6.7	7.2	6.6	7.6
20 kA, 8/20 µs	I_{surge}	*kA*	19.7	19.7	19.8	19.6	19.7
	V_{ter}	*kV*	896	900	882	898	886
	V_{res}	*kV*	354	351	340	343	341
	V_{tank}	*kV*	546	543	541	539	541
	V_{hv}	*kV*	359	366	555	477	617
	V_{neut}	*kV*	15	14.5	14.2	13.2	14.3
10 kA, 1.2/50 µs (Steep wave)	I_{surge}	*kA*	9.9	9.8	9.8	9.7	9.8
	V_{ter}	*kV*	609	647	1324	1229	1460
	V_{res}	*kV*	331	360	362	396	360
	V_{tank}	*kV*	317	300	273	281	277
	V_{hv}	*kV*	422	572	1237	1113	1365
	V_{neut}	*kV*	40	39	34	38	34
4 kA, 30/100 µs (Damped wave)	I_{surge}	*kA*	3.8	3.8	3.8	3.8	3.8
	V_{ter}	*kV*	230	230	230	231	230
	V_{res}	*kV*	122	122	122	122	122
	V_{tank}	*kV*	108	108	108	108	108
	V_{hv}	*kV*	122	123	123	123	123
	V_{neut}	*kV*	0.8	0.9	1.2	0.9	1.2

Table 5.2 : Summarized results of sensitivity analysis

5.5 Observation of results

5.5.1 Results analysis

By analyzing the simulation results it is basically seen that the surge currents get reduced in magnitude when it comes near the arrester. We have assumed that the surge occurs about 100 m away on the MV line and selected the modeling parameters accordingly, whereas in real case it would happen even farther, away from the transformer.

From table 5.2 it is seen that the surge with 5 kA magnitude (8/20 μs) do not create a big difference with the type of installation, still installations 3 and 5 create higher voltages between HV insulation (V_{hv}). Steeper waves create higher voltages always at the terminals. It is evident that 10 kA, 8/20 μs wave creates unusually high voltages between HV insulation and the steeper waveform of the same magnitude (10 kA, 1.2/50 μs) creates even higher voltages.

For surges higher than 5 kA, neutral voltage rises beyond 4kV with respect to ground. Insulation level of the LV side of the transformer is believed to be around 6 kV. It is observed that the LV insulation level is exceeded in almost all the cases.

It is observed that the installation arrangement 1 gives lowest voltages on the nodes. Arrangements 2 and 4 also look acceptable in most cases for surges with lower steepness. Arrangements 3 and 5 are creating high voltages for steeper waves hence those are detrimental to the transformer.

5.5.2 Outcome of the simulation

Installation arrangement 1 turns out to be the best. Depending on the practicability in installation, adoption of arrangement 2 and 4 can be recommended. Arrangements 3 and 5 have to be avoided.

As discussed under the section 4.2, in the Sri Lankan context, most probable surge current passing through an arrester would have magnitudes of 5 kA and lesser. However, there is a possibility of adding up currents, if more than one arrester gets activated, as the three arrester connections are connected to one lead for earthing. It is seen that almost all installation methods resist surges of 5 kA order, except the steeper ones. However, in all the cases LV insulation is stressed very much. This is detrimental to the transformer as well as to the consumer. Use of LV arresters would be a solution for this.

As far as above output results are obtained using simulations with assumed parameters, they may not be acceptable for absolute performance. However, they are good enough to compare different installation arrangements.

Chapter 6

Conclusion

It is seen that there are various reasons for transformer failures. In this study, main emphasis is given to the transformer installation practices presently followed by CEB. Above from all other reasons, transformer installation practice comes as the prime cause for transformer failures because through improper erection methods followed, undue voltages can appear on the transformer insulation and winding during lightning. These high stresses accelerate the effects caused by other reasons.

Out of the five installation arrangements analyzed in this study, arrangement 1 turns out to be the best. In this arrangement, arresters' flexible leads connect to the transformer tank at the top of the transformer. The arrester earth conductor runs separately to the earth, starting from the arresters' bottom terminals. This method needs to have a special clamp introduced where the three arresters' bottom terminals and the earth lead connect together. No separate connection done to the transformer tank, but the tank connection is achieved through the arresters' flexible lead connections. Although this arrangement exhibits good results, it may be difficult to adopt it in the field due to practical constraints. Any clamps introduced will have to ensure that the arresters' ground lead disconnectors are free to operate when arresters fail. Arresters with their ground lead disconnectors operated, must be clearly visible from the ground. Also this method needs to have an extra connecting clamp that brings more connections. Having more connections can adversely affect.

Considering the practicability, adoption of arrangements 2 and 4 will be acceptable, as for most of the common surges on our MV system those installations do not exert vey high voltages at the nodes.

In arrangement 2, the tank connection is done in a 'T' formation with the arrester earth lead using a proper compression connector ('C' clamp). This 'T' connection can be made even at a higher point on the arrester earth lead, so that the involved lead length will further be reduced. This method is presently being practiced in Western Province South II of CEB's Distribution Region 3.

Arrangement 4 is very simple, where the flexible leads of the three arresters connect to the transformer tank at the top and the tank and earth lead connects to the transformer tanks's connecting flange and continued to the earth. This method is acceptable for many common surges in the MV system. This is now practiced in some provinces of Distribution Region 2 of CEB. Considering the practicability and ease in adoption, this can be generalized for all transformer installations.

In the arrangements 3 and 5, arresters' earth lead and the transformer tanks' earth lead are laid separately and those connect to the earthing system at the ground level. These methods involve very high lead lengths. When conductor leads become long, having more bends are also inevitable. Bends introduce more inductance to the lead. Through analysis it is shown that those arrangements exert very high voltages at the nodes. Hence, those arrangements have to be avoided.

It is seen that in almost all the cases, LV insulation is stressed very much. This is detrimental to the transformer and also dangerous to the consumer. Use of LV arresters would be a solution for this. CEB has used LV arresters in the past and deviated to the present practice, to have transformer installations without LV arresters. This may be because of not having good quality arresters and not having a proper maintenance programme. CEB has to initiate installation of LV arresters in transformer installations, again.

Not only transformer installation practices, but also MV line installation practices have impact on transformer failures. The practice of having the overhead earth conductor under the medium voltage conductors does not serve much as a lightning shield. In a shielded path with trees and buildings, the position of the overhead earth wire may not have much effect, but in an exposed path, it is always better to have the overhead earth conductor drawn at the top of the pole, above the MV line. This is practiced in MV tower constructions. Hence, any misconception has to be addressed and proper erection practices have to be implemented.

When connecting arresters in a transformer installation, proper care must be taken to connect it near the transformer. As now the transformers come with the arrester mounting bracket fixed to its tank, proper installation of the arrester is followed automatically in new installations. In earlier installations, arresters are mounted at a considerable distance from the transformer. Breakdown gangs can be properly instructed to replace those with an improvised way to have the arresters mounted on the transformer tank.

It is revealed that fixing of arresters on the MV line to reduce surge impacts to be a misconception. Although this reduces the voltage at the arrester connecting point during a surge, it causes very high voltages to appear on the either sides of the line, due to reflections. An arrester always has to be fixed near the equipment to be protected.

Condition monitoring of the arresters have to be carried out with proper instruments such as thermal cameras, so that any near-failure arrester can be detected and replaced before it fails and creates a problem to the transformer to which it is connected.

When selecting auxiliary gear such as drop down lift off switches (DDLO), arresters and fuses, proper care must be observed to select with proper ratings and good quality. It is seen that most of the DDLOs presently employed are not rated to our MV system. Sometimes arrester classification and ratings become not sufficient to serve special situations. In such occassions, different classes of arresters can be employed after doing a case by case analysis. Quality of the arresters used is also a matter to ponder. Specifications of arresters and DDLOs have to be revised to allow properly rated and good quality items to be procured.

CEB has to pay attention to do way leave function effectively so that intermittent earth faults are minimized. Also load balancing has to be carried out periodically. Overloaded transformers have to be identified timely and necessary augmentation work has to be planned. Proper coordination of fuses and auto recloses will minimize unnecessary surges on the transformers.

Management of transformer movement is also an area that CEB has to pay attention. Sometimes those transformers got repaired from the factory are not identified properly, when re-installed. Any defect with functional drawbacks can appear with the repaired transformers, but due to not having a proper database, those would not have been recognized. Most of the time CEB looses the warranty offered by the manufacturer due to poor management of transformers.

CEB presently is not following routine inspection on transformers. Early replacement or repair of certain visible defects such as bushing failures and oil leaks from gaskets are not promptly attended. Due to theft, sometimes transformers operate without copper earth conductors. Sometimes it is seen that failed lightning arresters also remain unnoticed. Hence routine inspection has to be done properly and any possible defects have to be attended early. Also transformer failures have to be studied case by case and proper solutions be made.

In order to avoid theft of copper cables, usage of copper clad steel for earth cables can be investigated. As it is not possible to extract copper from those cables, theft will eventually stop. Since the lightning current flows only along the skin of the conductor, copper clad steel cables with proper size and impedance will be suitable to be used for the earth conductor. It has to be analyzed whether the selected size is suitable for LV neutral earth and whether capable for handling earth fault currents as well.

It is shown in this report that the presently followed grounding method is not effective enough to lower the earth resistance in transformer installations. Hence, it has to be revised. Instead of using the construction concrete mix for the earth block, having a mixture with more conductive elements can be investigated. As suggested in the section 3.2.3 of this report, laying the horizontal part of the earth conductor without insulation will definitely have an improvement on the earth impulse impedance. It is not only the measured DC earth resistance value what matters for the impulse resistance, but also the structural profile of the earthing system. Having smooth surfaces on the concrete block will contribute to lower the impulse resistance. The initiated research and development work can be continued to propose an effective earthing method.

When laying arrester and neutral earthing systems, proper attention must be paid to keep at least 3 m separation between the two earths to avoid overlapping of earth zones. Also when drawing the lightning arrester earth and the LV neutral earth conductors along the pole, fixing those much apart is important to avoid electromagnetic coupling.

It has been found that improper connecting methods are being followed in transformer installations. Sometimes the earth cable and rod connection is done with a locally made clamp. Use of improper material can cause galvanic corrosion at the joint and will end up with a weak connection. During surge diversion, very high voltages may appear at these joints due to high resistance, causing the transformer insulation to undergo very high stresses. Presently used exothermic welding method is good enough, provided that better quality exothermic powder is being used and the mould is properly handled. Cleaning of the mould after use is very important. In the earth leads, connections and bends have to be avoided as far as possible as they introduce higher inductance that will cause to generate very high voltages when a surge current flows.

I addition to the lead connecting methods proposed in this study, many simple practices as explained above can be adopted to improve the quality of transformer installations, so that the CEB's distribution transformer failures can be drastically reduced.

References

[1] Chief Engineer (Energy Management – NWP) – CEB, Study on transformer failure MV/LV in CEB and cause of action, Energy and Quality Management Branch NWP, CEB, September 2009

[2] Chairman Distribution Co-ordination Committee, CEB, 2010 Catalogue & price list of materials, RE Projects & Procurement Branch, CEB, 2010

[3] Andreas Ebner, "Transient transformer inrush currents due to closing time and residual flux measurement deviations if controlled switching is used", ETH Zurich, Switzerland

[4] D. Fulchiron, "Cahier technique no. 192 Protection of MV/LV substation transformers", Groupe Schneider, 1998, pp. 3-9

[5] V.B. Wijekoon, Improvement of life expectancy of oil-immersed transformers with practical case studies on Laxapana (Stage II) and Polpitiya generator transformers, report submitted to Institution of Engineers Sri Lanka for professional review, December 2005

[6] J.R. Lucas, and D.A.J. Nanayakkara, "Lightning protection of pole mounted transformers and its applications in Sri Lanka", Transactions of IEEE Sri Lanka, April 2001

[7] T.A. Short, Power distribution handbook. CRC Press, 2004

[8] M.J. Manyahi, R. Thottappillil and A. Nzali, "Some reflections on the lightning protection of power distribution transformers in Tanzania", 2nd International conference on Electrical Engineering and Technology, Dar-es-Salaam, Tanzania, September 2011

[9] ABB High Voltage Technologies Ltd, Application guidelines - Overvoltage protection: Dimensioning, testing and application of metal oxide surge arresters in medium voltage systems, Switzerland, 2009

[10] J.R. Lucas, "High Voltage Engineering", Lecture notes on lightning phenomena, 2001, http://elect.mrt.ac.lk/HV_Chap3.pdf

[11] IEC 60071-1: 2006-01 "Insulation co-ordination – Part 1: Definitions, principles and rules", Edition 8.0

[12] Power Quality and Utilization Guide, Leonardo Energy, Voltage Disturbances, Transient and Temporary Overvoltages and Currents, Clause 5 – Lightning Surges, June 2007 http://www.leonardo-energy.org/webfm_send/199

[13] CEB specification – 011:2008 : Medium voltage surge arresters, 2008

[14] Nay Kyi Htwe, "Analysis and design selection of lightning arrester for distribution substation", World Academy of Science Engineering and Technology, 2008

[15] Volker Hinrichsen, Metal Oxide Surge Arrester- Fundamentals, 1st Edition, Siemens AG, Berlin, Germany, July 2001

[16] IEC 60099-5 : 2000-03 "Surge Arresters – Part 5 : Selection and application recommendations", Edition 1.1

[17] IEEE Surge Protective Devices Committee, WG 3.4.11, Surge arrester modelling techniques, Memphis Tennessee, September 1983

[18] C. Chimklai and J.R. Marti, "Simplified three-phase transformer model for electromagnetic transient studies", The University of British Colombia, Vancouver, Canada, IEEE Transactions on Power Delivery, vol. 10, No. 3, July 1995

[19] Website of "Lightning preventor of America", Manufacturer's standard HBP-21, http://www.lightningpreventor.com/manufacturers-standard.shtml

[20] Mike Holt's Internet forum on "Grounding conductor sizing", http://forums.mikeholt.com/archive/index.php/t-57205.html

[21] Eilert Bjerkan, High frequency modeling of power transformers - stresses and diagnostics, Doctoral Thesis, Faculty of Information Technology, Mathematics and Electrical Engineering, Norwegian University of science and technology ISBN 82-471-6923-1, May 2005

[22] San-Earth Technical review, Practical measures for lowering resistance to grounding, Sankosha Corporation http://www.sankosha-usa.com/pdf/san-earth-tech.pdf

[23] Peter Fong, Moisture Estimation in Transformer Insulation, Omicron Electronics Corp. USA, November 2009 http://www.nwppa.org/web/presentations/09_AK_Conf/Moisture_Estimation_OMICRON.pdf

[24] C. Andrieu, E. Dauphant and D. Boss, "A frequency-dependent model for a MV/LV transformer", International Conference on Power Systems Transients, Budapest, Hungary, June 1999

[25] K. Pedersen, M.E. Lunow, J. Holboell, and M. Henriksen, "Detailed high frequency models of various winding types in power transformers", International Conference on Power Systems Transients, Montreal, Canada, June 2005

[26] PSCAD version 4.2.1 Eval – Steep front model, Manitoba HVDC research centre, August 2006

Appendix I

Photographs of laying out improved earthing methods

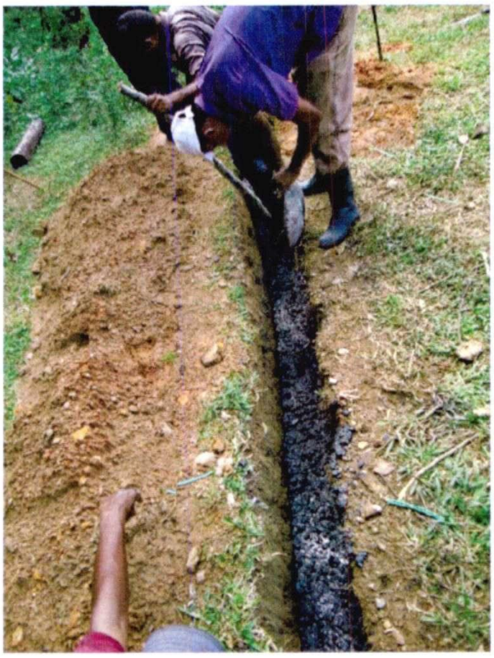
(Original is in colour)

Pit dug for installing the earth

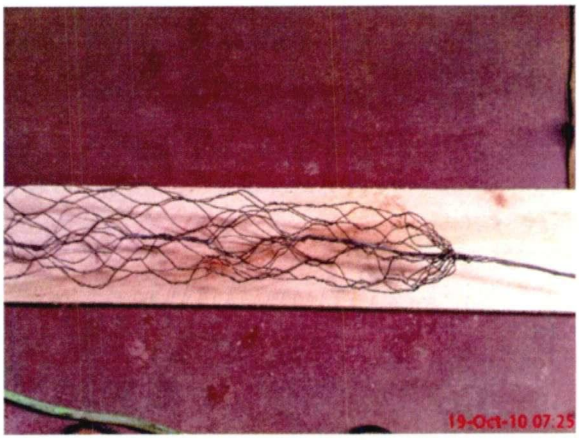
Pre cast earth cylinder

Exothermic Welding of the copper Conductor

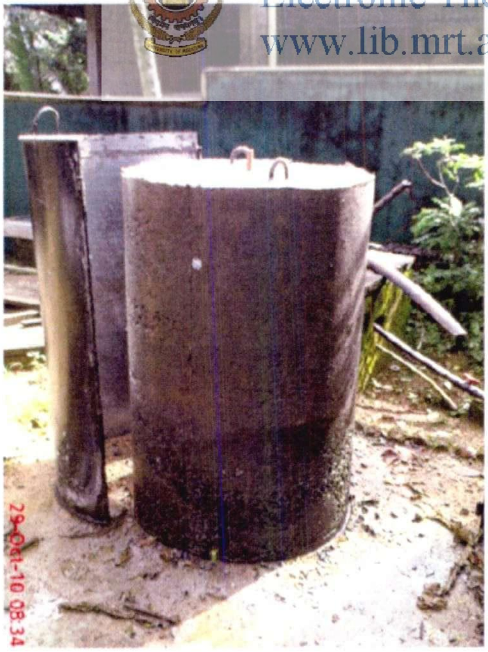
Laying the horizontal cable part



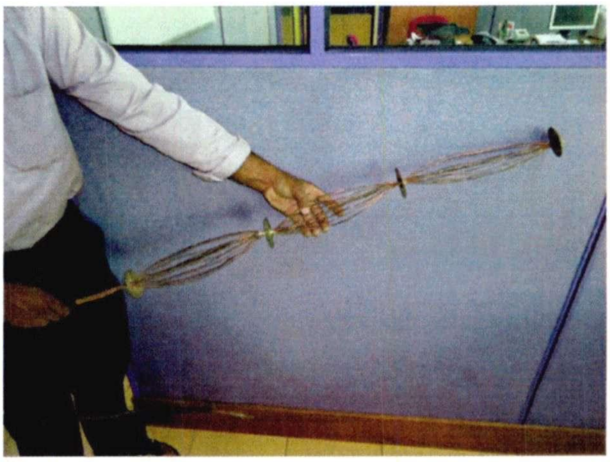
Covering the horizontal cable part with conductive concrete mixture



Copper conductor outer strands made to rectangular mesh shape to be laid inside the cylinder – no joints



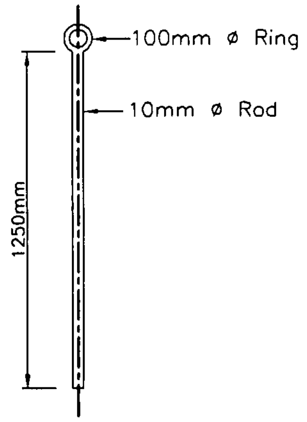
Presently used meshed concrete block pre cast at site to obtain a smooth surface



Copper conductor outer strands separated to be laid inside the cylinder – no joints

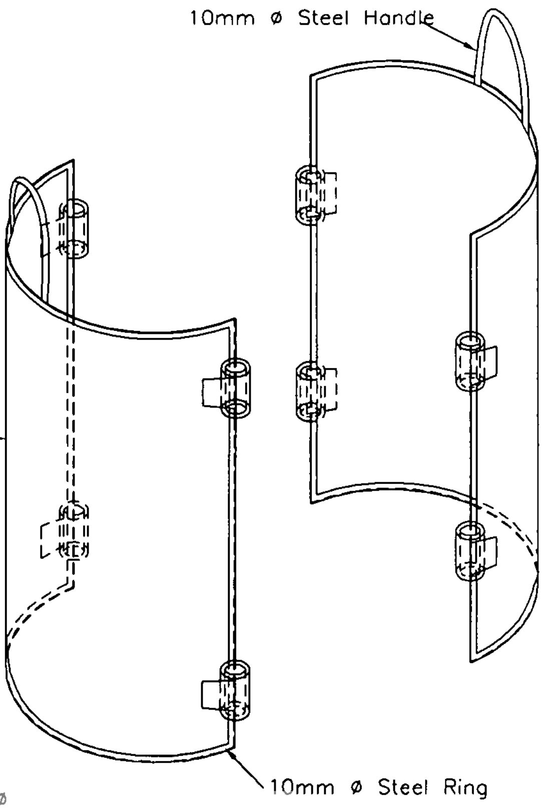
Appendix II

METAL SHUTTERING FOR CONCRETE EARTH BLOCK

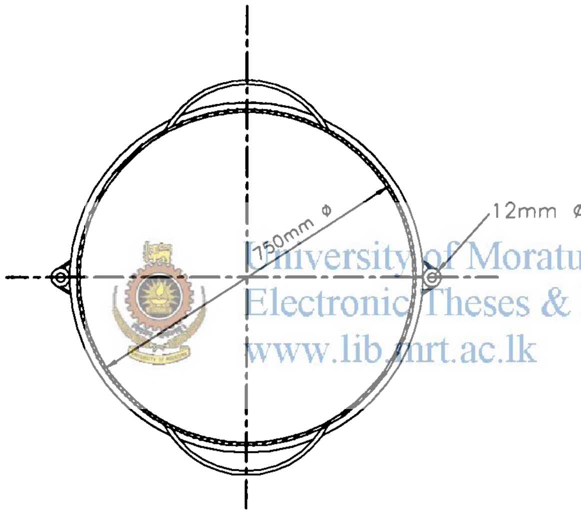


10mm Ø ROD

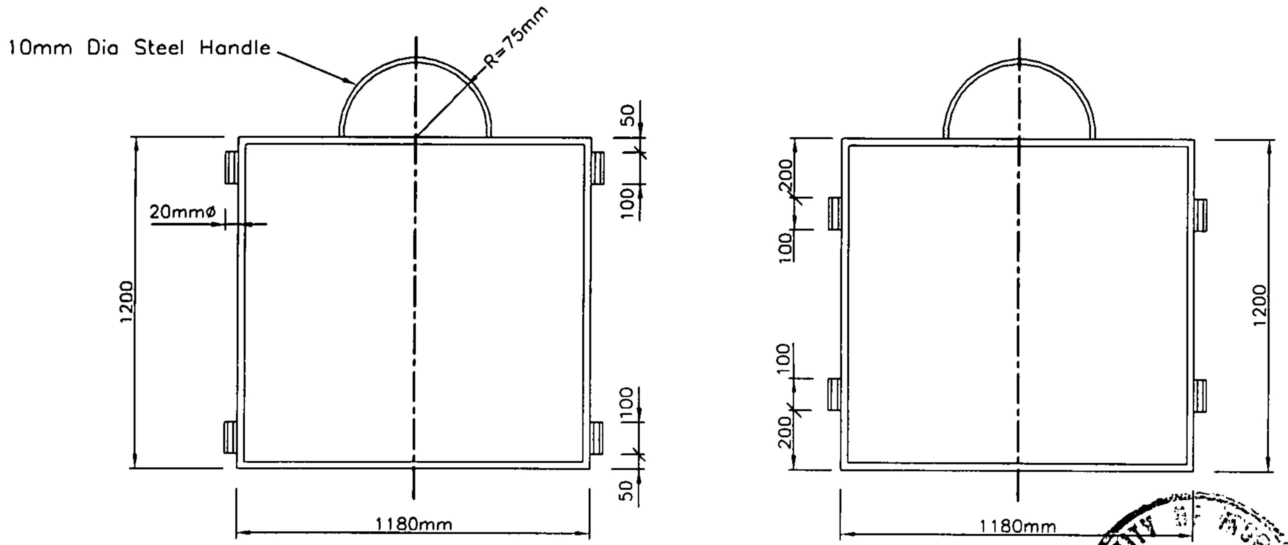
(2 Nos)



ISOMETRIC VIEW



PLAN

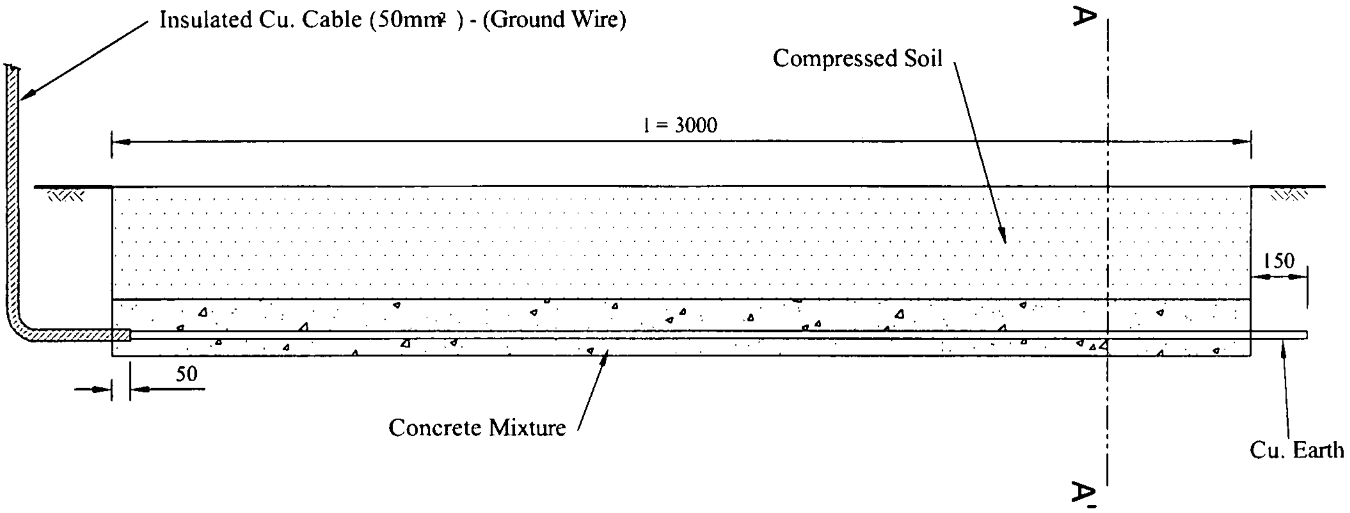


DEVELOPMENT

Appendix III

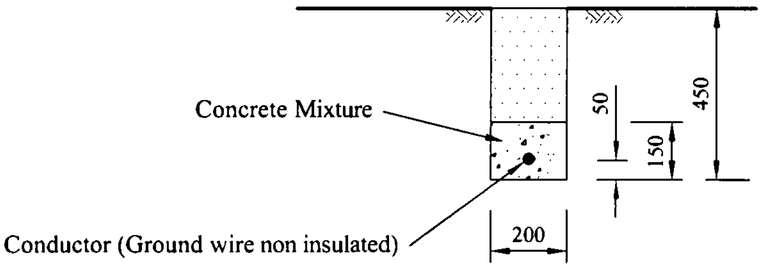
PROPOSED EARTHING SYSTEM

01) (a)



Cross section (1) a

(b)



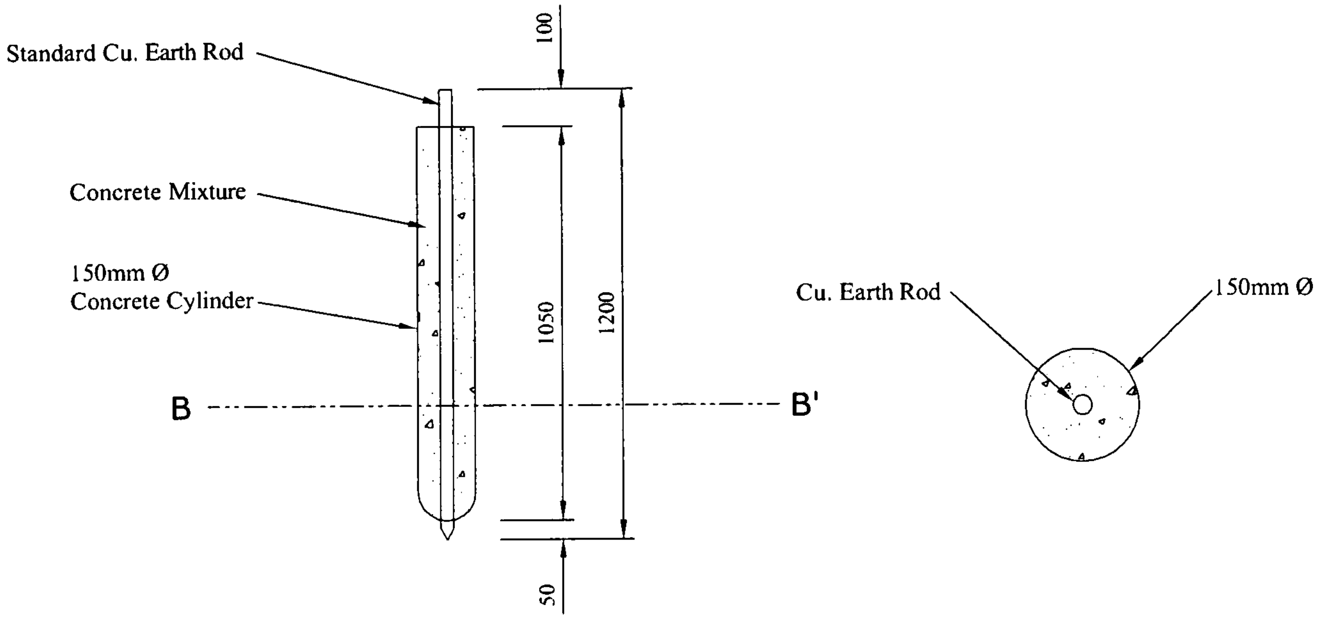
Cross section (1) a

(Section AA')

Horizontal Earth Conductor Profile

Scale - 1:20

02) (a)



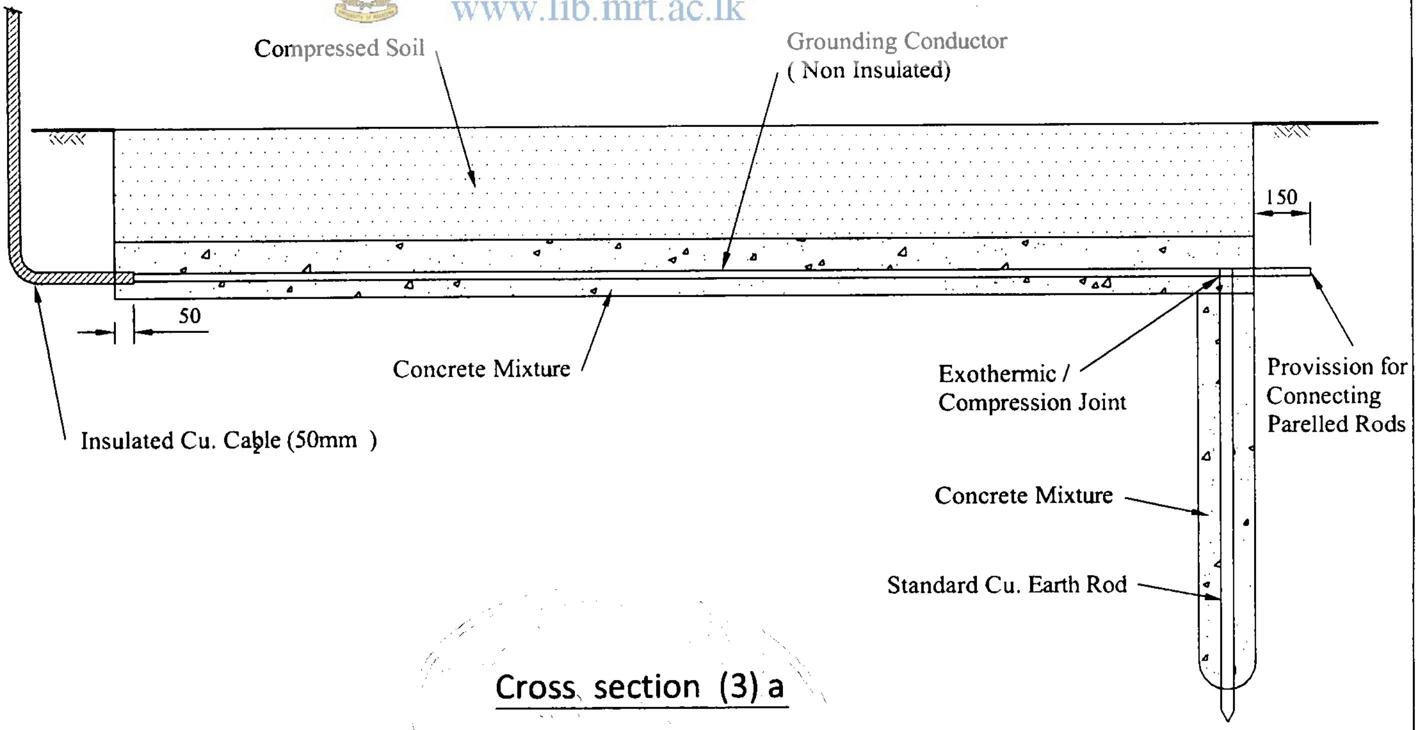
Cross section (2) a

Cross section (2) b
(Section BB')

Concrete Earth Cylinder

Scale - 1:10

03) (a)



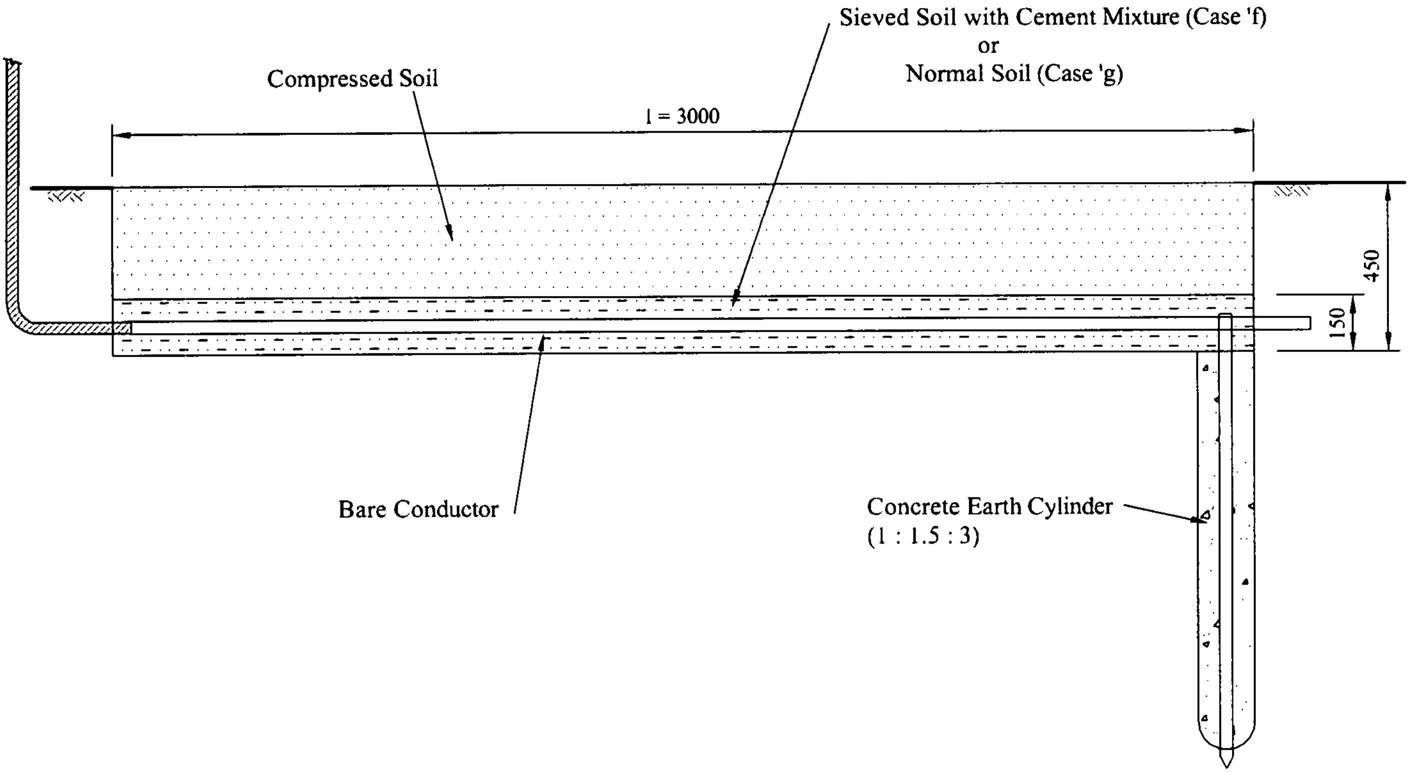
Cross section (3) a

Horizontal Earth Conductor with Concrete Earth Cylinder

Scale - 1:20

Appendix V

03) (b)



Cross section (3) b

Horizontal Conductor with Soil and Cement Mixture and Concrete Earth Cylinder

Scale - 1:20

For Earth Resistance Measurement Following Methods Can be Used

01) Horizontal Grounding Conductor with Earth Cylinder
Cross section as shown in figure 03 (a)

a) Cement - 1 Sand - 2 Granite - 4 Normal Mixture

b) Cement - 1 Sand - 2 Granite - 4 Graphite - 0.25

c) Cement - 1 Sand - 2 Granite - 4 Bentonite - 0.25

d) Cement - 1 Sand - 1.5 Granite - 3

e) Cement - 1 Sand - 1.5 Granite - 3 BBQ Charcoal Powder

f) Sieved Red Soil - 2 Cement - 1 (1 : 1.5 : 3) Concrete Cylinder

g) Cement-1, Sand-2, Granite-4, Coal Powder-0.25 for horizontal part & (1 : 1.5 : 3) Concrete Cylinder

h) Earth rod driven into ground without concreting with insulated horizontal conductor part

i) Earth rod driven into ground without concreting with bare horizontal conductor part

j) Same as above (i) with l = 4000m

k) Bare copper tape 25mm x 3mm, 3m Length only for horizontal part. (No concreting)

l) Single bare conductor used for cylinder and horizontal part (Mixture - 1:1.5:3)

m) Bare conductor used for cylinder, no horizontal part.(Mixture - 1:1.5:3)