ANALYSIS OF TRANSIENT OVERVOLTAGE IN MEDIUM VOLTAGE DISTRIBUTION NETWORK OF CEYLON ELECTRICITY BOARD

A dissertation submitted to the
Department of Electrical Engineering, University of Moratuwa
in partial fulfillment of the requirements for the
degree of Master of Science

by
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Abstract

This thesis presents the analysis of transient overvoltages in medium voltage (33kV) network and the research is based on feeder lines in the Uva province. Parameters which influence lightning performance of overhead distribution lines such as line height, line length, type of structure, availability of shield wire and flash density in the area are discussed in details. More over, failures due to transient overvoltages and its impact on the reliability of the network are analyzed in this study.

Lightning may cause flashovers from direct strokes or induced voltage from nearby strokes. Direct lightning to power distribution lines causes insulation flashovers in great majority of the cases. Therefore the goal of this research is to estimate the lightning performance level of feeder lines and investigate improvements. Shielding effect from nearby trees, critical flashover voltages for different flashover paths and deterioration of insulation with aging are also discussed. Thus the analysis of lightning related incidents such as transformer failures, arrester failures and nuisance fuse blows are presented.

The study of transformer installation reveals that arrester lead length becomes critical during a lightning discharge since it generates high voltage stress in the winding which may fail the distribution transformer. Earth rod impulse resistance is also an important parameter which increases the voltage stress.

It is necessary to develop models, using, electrical parameters for simulation of transient overvoltages. The PSCAD software is especially developed to study transient simulations of power systems. Variation of transient overvoltages due to strikes to phase wires, strikes to earth wire, and variation due to striking distance are discussed in this study. Further, simulation of surge arrester performance and nuisance fuse blows are also presented. Finally, the study presents applications to achieve zero lead length in substation, introduction of surge durable fuses and procedures which can be implemented to improve lightning performance in the MV network.

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.

UOM Verified Signature

W.A.V Weerawardena

21.01.2010
Date

We/I endorse the declaration by the candidate.

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List of principal symbols

CEB: Ceylon Electricity Board

CSC: Consumer Service Center

CFO: Critical Flashover

DDLO: HT fuse link

E/F: Earth Fault

GFD: Ground Flash Density

HT: High tension

HV: High Voltage

LA: Lightning Arrester

LT: Low Tension

LV: Low Voltage

MV: Medium Voltage

MSL: Mean Sea Level

O/C: Over Current

PQ: Power Quality

PSCAD: Power System Computer Aided Design

T/F: Transformer

TOV: Transient Overvoltage

Chapter 1

Introduction

During recent years, electricity customers expect a better quality of electricity supply. The advent of an information age heavily dependent on digital electronics technology has brought with it recognition that power quality (PQ) has become an important technical-economic issue for both electricity suppliers and many of their customers.

There are three main classes of power quality disturbances:

– Voltage disturbances, waveform distortion and transients.

Transient overvoltages in electrical transmission and distribution networks result from the unavoidable effects of lightning strikes and network switching operations. These overvoltages have the potential to result in large financial losses each year due to damaged equipment and lost production. Transient overvoltages can be defined as one of the power quality problem and can be classified as being either impulsive (transients resulting from lightning strikes) or oscillatory (transients resulting from network switching). These transients move through the distribution network in different ways depending on their frequency content. The lower frequency oscillatory transients propagate in essentially the same way as the 50 Hz fundamental voltage. However, impulsive transients tend to move in a very different way which can give unexpected consequences. A full study of their effects requires travelling wave analysis.

Lightning is an electrical discharge in the air between clouds, between different charge centers within the same cloud, or between cloud and earth (or earthed object). Even though more discharges occur between or within clouds, there are enough strokes that terminate on the earth and cause problems to power systems. When lightning strikes occur in or near an electricity distribution system, lightning currents are generated and conducted through the power system into connected equipment. Large impulsive transient overvoltages are produced as a result of this current flow. Lightning can strike directly to the phase conductors of overhead power lines producing very high magnitude transient overvoltages. Peak current can be up to 200 kA with voltages over 1 MV.

This situation usually causes power system faults that eventuate into supply interruptions and voltage sags throughout the distribution network. Lightning can also strike the overhead earth wire (shield wire) that is sometimes installed above the phase conductors to protect them from a direct lightning strike, or the tower or power pole itself. This can lead to what is known as a back-flashover to the phase conductors as the voltage on the earth wire or tower rises to become much greater than the voltage on the phase conductors. In addition to direct strikes, lightning can induce currents and voltages on power lines without touching them (known as an indirect strike). The large electromagnetic fields produced by lightning discharges can couple into the power network and produce induced transients. Lightning surges originate beyond human control, and their severity depends on many parameters determined by the point of impact of the lightning stroke and by the structure of the power system.

However, while the structure of the power system is under human control, its parameters are generally determined by considerations other than lightning protection. Medium voltage (MV) distribution network of Ceylon Electricity Board (CEB) consists of 33 kV and 11 kV lines. The entire operation of CEB distribution is divided into four regions and each region comprises of two to three provinces. The Region 3 of CEB consists of three provinces namely, Western Province South 2, Sabaragamuwa and Uva.

Uva province lies in the central part of the country. A large geographical variation can be seen throughout the province. Many waterfalls, mountains and difficult terrains are located within the province. Tea plantation is the main industry prevailing in the province while there are few other industries such as agriculture, manufacturing of sugar, garments etc. Tourism is also another important industry of the province especially in Nuwara Eliya and Badulla districts. MV network of Uva province consists with about 2444 km length of 33 kV feeder lines which spread over three districts, namely Badulla, Monaragala & Nuwaraeliya. As the consumers are dispersed over the entire province with larger geographic area, the overhead feeders are running long distances through jungle, semi jungle, forest reserve, paddy field, and urban and rural village areas. Thus the lines are frequently exposed to natural disturbances like lightning.

Medium voltage feeder tripping analysis shows that breaker trippings due to earth fault and over current are more than hundred per month, especially in the bad whether conditions like heavy rain. Although, it is assumed that the main reason for these trippings is touching of way leaves causing earth faults, the assumption is not valid due to the fact that the number of insulators to be replaced after the bad weather season is high. Further it is observed that a large number of distribution transformers are damaged during this period causing heavy financial losses to CEB.

Thus the major contribution for line tripping could be flashovers of insulators due to transient overvoltages in the MV network caused by lightning. The larger number of trippings degrades the quality of power supply to consumers and that will affect the image of the CEB. Further quality of supply causes heavy financial losses to CEB as well as to the consumers.

Since a detail study of failure analysis of MV network related to transient overvoltages has not been done for the Uva province, an analysis on transient over voltage of MV network and proposing any mitigatory methods will be a good contribution for the improvement of reliability. Thus this research area has greatly motivated me to carry out a study on the above topic. Further I hope this is a part of my responsibility as Chief Engineer (Distribution Maintenance) of Uva province, who's responsible to carry out maintenance work in the MV network and to maintain the reliability and quality of the medium voltage supply.

1.1 Scope of Study

The main scope of this project is to study the behaviour of transient overvoltages in the medium voltage distribution network and identify relevant areas to be modified to improve the lightning and transient performance of the distribution network which includes:

- Study of MV network configurations in the Uva province
- Study of feeder failures and causes of outages
- Identification of a sample and data collection for the same
- Calculation of lightning performance of distribution feeder lines
- Study of shielding effect from near by trees
- Study of critical flashover (CFO) voltages for different flashover paths
- Measurement of flashover voltage of collected samples of insulators
- Study of TOV variation using computer models
- Proposals for improvements and modifications to the system

1.2 Literature Review

Over the past 40 years or more, fully-fledged studies and research have been conducted all over the world on transient overvoltage in MV distribution lines, lightning phenomena, surge arresters and computer simulation. The fruits of such labours have made their way into lightning protection design guidelines at different times. As research advances, the number of lightning outages has been steadily falling, but lightning outages still account for a high percentage of failures on high voltage distribution lines.

The Reference [1], "Lightning Protection evaluation and management risk", describes impact of lightning flashes and method to evaluate number of lightning flashes. Data of thunder days in different meteorological stations in Sri Lanka is given in this document.

Lightning induced over voltages on power distribution lines, surge arrester behavior due to lightning induced voltages and magnitude of induced over voltages have been discussed in Reference [2], "Lightning-Induced Overvoltage".

The source [3] "Lightning Protection of Overhead Power Distribution Lines" discusses the effect of lightning on distribution lines, transient overvoltages in lines and benefits of arrester installation.

Types of lightning stresses, calculation of number of direct strikes to an overhead line and protection methods are discussed in Reference [4] "Lightning and HV electrical installations".

"Lightning phenomena", Chapter 3, Reference [5] discusses mechanism of lightning, calculation of shielding angle of feeder line and traveling wave theory.

IEEE Standard 1410, "Guide for improving the lightning performance of electrical power overhead distribution lines", Reference [6] contains information on methods to improve the lightning performance of overhead distribution lines. This guide identifies factors that contribute to lightning caused faults on overhead distribution lines and suggest improvements to existing and new constructions.

Reference [7], "Introduction to PSCAD/EMTDC Version3" of Manitoba HVDC Research Center is a workbook designed to guide the user of PSCAD/EMTDC software through the use and application of PSCAD. This course material is prepared to help electrical power engineer into useful and essential studies of power systems and controls.

Properties of insulators and mechanism of surface flashovers are discussed in Reference [8], "Electrostatic and electrodynamics field analysis of 33 kV line insulators".

Types of fuses, reasons for nuisance fuse blows and improvements in fuse technology are contained in the Reference [9], "Protective equipment update" of Cooper power systems. Nuisance fuse blowing is also discussed in Reference [10].

New equipments improved for mitigation of transient faults are presents in Reference [11], "Lightning Protection Product" of Live Line Technology.

Reference [12], "Lightning Induced Overvoltage on Overhead Distribution Lines" discusses the reduction of induced voltage stress by application of shield wire.

Distribution standards and specification for MV pole lines and guide line for distribution system earthings are described in Reference [13] and Reference [14].

Reference [15]. "Activity of Cloud-to-Ground Lightning Observed in Sri Lanka" describes activity of cloud –to- ground lightning flashes observed during the monsoon thunderstorms over Sri Lanka with a lightning locating system consisting of two direction finders (DF). It also gives details of percentage of positive and negative flashes, average peak current and flash densities observed in different locations.

Findings from tests and inspections of arresters withdrawn from service, the results of laboratory studies with multipulse lightning currents and high temporary over-voltages, and comparisons of in-service and laboratory failure modes are described in Reference [16], "Studies of In-service and Laboratory Failures of Metal Oxide Distribution Surge Arresters".

Study of lightning performance of quadruple circuit transmission line behaviour towards lightning performance using ATP-EMTP simulation program is presented in the Reference [17]. Models use for surge arresters, overhead lines, towers and insulators are also discussed in this paper.

Chapter 2

Statement of Problem

2.1 Identification of the Problem

Large number of feeder tripping in MV network of Uva province has substantially degraded the reliability and quality of the CEB power supply. Lack of attention to identify the cause of tripping has further aggravated the said problem and lot of consumer complaints from various part of the province are daily received. Thus, the CEB can't have a blind eye to the said complaint further as this will severely affect the day to day operation of CEB. There are many reasons why the consumers are not tolerated as in the past. The need for reliable electric power supply for thousands of consumer electronic products and sensitive manufacturing processes is growing more today than ever before. Minimizing the effects of transient overvoltage to power transmission and distribution lines is a major goal for every utility. This is paramount importance since momentary outages lasting even for a few milliseconds can trip machinery offline and cause financial and logistical headaches for many customers.

Behavioural pattern and performance of MV network during transient overvoltage depends on parameters such as line configuration, Basic Insulation Levels (BIL) of equipments, application of surge arresters, availability of shield wires, lightning flash density, earth rod resistance and soil resistivity, etc. Thus this research is carried out to assess operational aspects of MV network and to evaluate characteristics of transient overvoltage of CEB MV overhead line network. Finally based on the analysis mitigating solutions are proposed to improve the reliability and to enhance power quality.

2.2 Study of MV Network Configurations in the Uva Province

Uva province of CEB falls under the Distribution Region 3. It consists of four operational areas namely Badulla, Diyatalawa, Monaragala & Nuwara Eliya. These four areas are within the administrative districts Badulla, Monaragala & Nuwara Eliya. Uva province lies in the central part of the country. A large geographical variation can be seen throughout the province. Many waterfalls, mountains, tea plantations and difficult terrains are located within the province.

The existing medium voltage network of the province solely consists of 33 kV lines. Six 33 kV feeders are originated from Badulla 132/33 kV Grid Substation (GSS) and six 33 kV feeders are emanated from Nuwara Eliya 132/33 kV Grid Substation. In addition to this there are seven feeders originating from four grid substations in the adjoining provinces. Table 2.1 summarizes the details of existing distribution network of the Uva province.

Area	**LT Line Length Km**	**HT Line Length Km**	**Number of Substations**
Badulla	1889	591	375
Diyatalawa	1996	625	333
Nuwaraelliya	2086	653	407
Monaragala	1086	339	266
Total	**7057**	**2208**	**1381**

Table 2.1- Break up of existing distribution network of the Uva province

The existing MV overhead lines made up of various lengths with different tower and pole configurations and erected through different terrains serving their electrical loads. Some overhead lines in the system are installed on high ridges which are predominant in the region exposing and making them vulnerable to lightning.

To study the behavioural pattern of transient overvoltages in over head lines, following data such as feeder lengths, type of structure (Tower, Concrete pole or Wooden pole) and their heights, span lengths, availability of shield wire and their position, shielding angle, grounding rod resistance, soil resistivity, surge arrester availability and BIL values of each components were studied. The 33 kV network consists of 1914 km length of Raccoon conductors, 40 km length of Lynx conductors, and 450 km length of Weasel conductors. The shield wire of the 33 kV pole lines is fixed under the phase wire. Table 2.2 shows the basic data of existing 33kV feeder lines [13].

Type of Structure	Average Height	Line Arrang-ement	Shield Wire Availability	Number of Insulators	
				Tension	Suspension/ Post
Tower	14m	Delta	Over built	3	3
Lattice Pole	11m	Delta	Over built	3	1
Steel Pole	9.2m	Flat	Under built	3	1
Concrete Pole	9.2m	Flat	Under built	3	1
Wooden Pole	9.2m	Flat	Under built	3	1

Table 2.2- Details of 33kV feeder lines

Out of six feeders starting from Badulla Grid Substation, Namunukula feeder was selected as the sample feeder line for this research, which feeds load centers in different geographical areas. This feeder line has total line length of 274 km and consists of tower, concrete and wooden pole structures. About 80% of its line length covers high altitude areas (800 m to 1500 m above MSL) such as Badulla, Passara, Ella and Banadarwela. Meteorological stations at Badulla and Bandarwela record their lightning flash densities as 92 and 144 thunder days respectively [1].

Remaining part of the feeder line lies in lower elevation areas (less than 200m above MSL) such as Wellawaya, Buttala and Thanamalwila. The data recorded at the meteorological station in Hamanthota (52 Thunder days) can be considered as flash density in the said areas. A line length of 88 km from Badulla to Thanamalwila can be considered as the main feeder line. Remaining length of 186 km consists with large number of spur lines with different line lengths connected to the main feeder line. Fig. 2.1 shows the geographical illustration of the Namunukula feeder and indicates various lengths of spur lines connected to the main feeder.

Variation of soil resistivity at different elevation is illustrated in the Fig. 2.2.

The main feeder is protected from E/F and O/C faults by the circuit breaker installed at Badulla Grid Substation. Two Auto Recloser units are fixed at strategic places to protect the feeder from downstream faults. Lengthy spur lines are connected through a DDLO fuse which is rated for electrical loads in downstream.

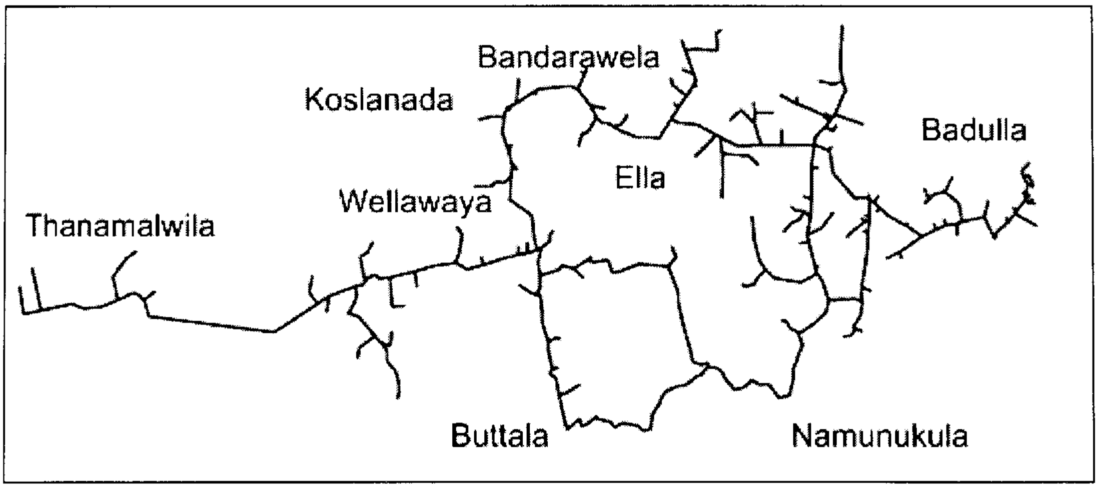

Fig. 2.1- Geographical illustration of the Namunukula feeder

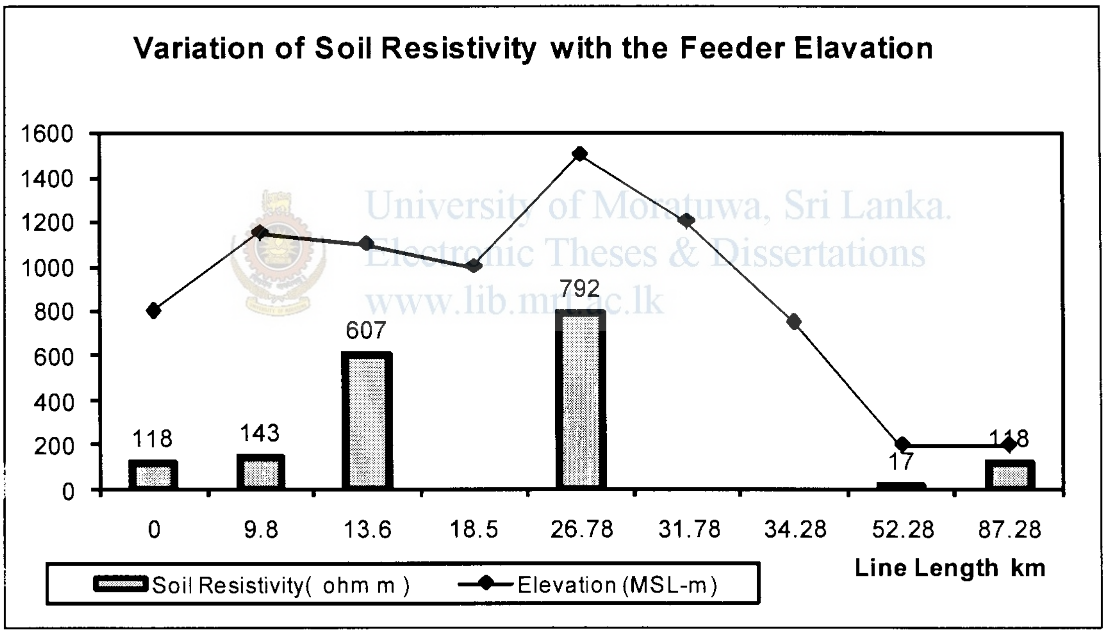

Fig. 2.2- Variation of soil resistivity with the feeder elevation

This feeder is made up of tower and pole lines.The main feeder from Badulla to Wellawaya consist of tower structures and the remaining part with concreate and wooden poles. Due to the variation of line height, insulation levels and availability of shield wire, performance against transient overvoltages differ from tower line to pole line. The major part of the Namunukula feeder (72% of it's total length) consist of pole lines and propotion of tower line to pole line can be illustrated as in the Fig. 2.3.

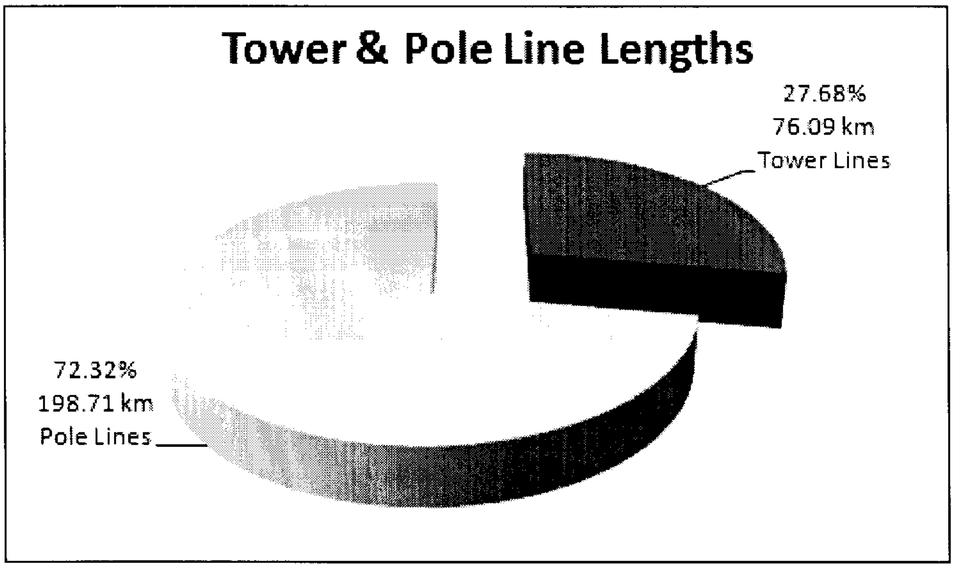

Fig. 2.3- Tower and pole line lengths of the Namunukula feeder

Also, it is important to identify the number of spur lines and their lengths to understand the behaviour of transient overvoltges and details are shown in the Fig. 2.4.

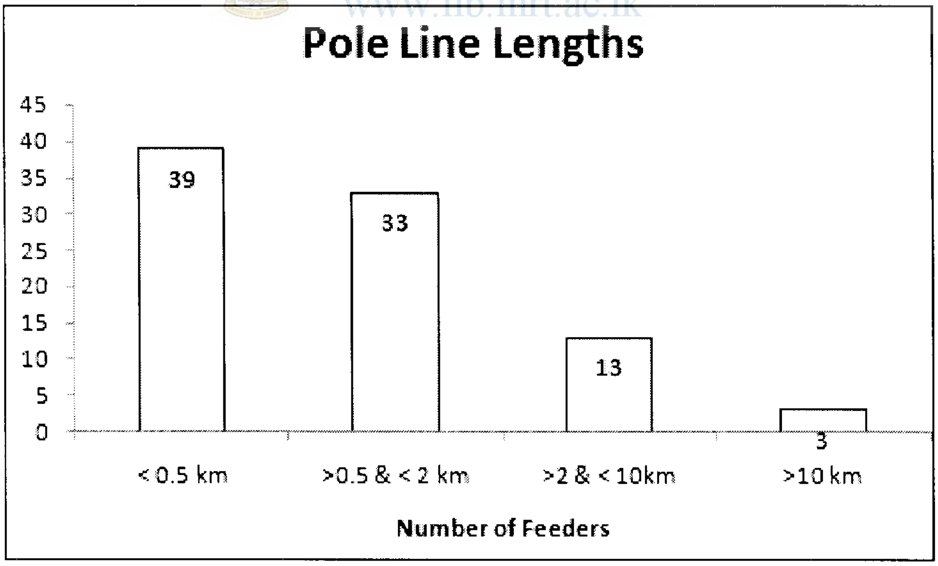

Fig. 2.4- Spur line lengths of the Namunukula feeder

These data reveals that Namunukula feeder consists with large number of spur lines having short lengths, but it can be seen that over 10 km length spur lines are also available.

Overhead shield wire is available in most of tower lines. Shield wires are grounded conductors to intercept lightning strokes so they cannot directly strike the phase conductors. Typically the line is considered to be effectively shielded when the angle between the line from the overhead shield wire to protected conductor and the vertical is less than forty five degree. [4].

Lightning may have a significant effect on a line's reliability, especially if its poles are higher than the surrounding terrain. More flashes are collected by taller structures. Since pole lines are comparatively lower than the tower lines and considered as shielded by nearby taller trees, the earth wire is designed to fix under the phase wires in pole lines. Phase wires of pole lines (Spur lines) are directly connected to phase wires of the main feeder. DDLO fuse links are used in some spur lines to protect them from earth faults. Due to installation difficulties, under built earth wire of pole line is not connected to the shield wire of tower line but connect to the tower structure. The way of connecting spur line (Pole line) to a tower line is illustrated in the Fig. 2.5.

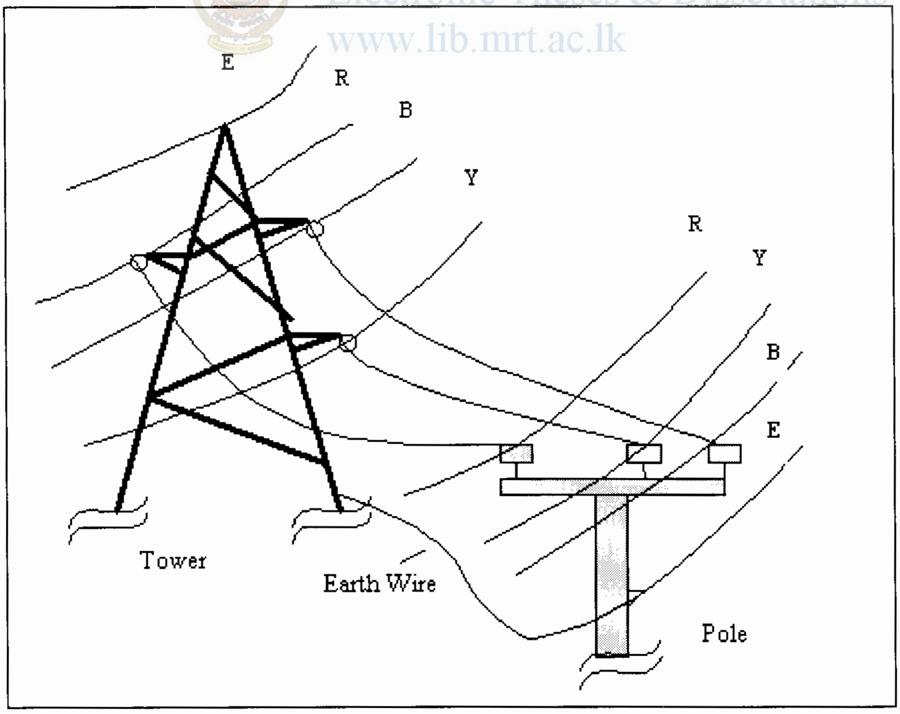

Fig. 2.5- Tower and pole line connection

2.3 Bad Weather and Pattern of MV Feeder Failures

Some overhead lines in the system are installed on high ridges which are predominant in this region, exposing and making them vulnerable to lightning. Overhead lines that are much longer and having more spur lines are also seems to be less reliable. Thus the analysis is focused in this research on following areas based on failure reports.

- Causes for failures
- Effect of whether related phenomena
- Specific areas vulnerable to transient overvoltages and
- Specific equipments vulnerable to transient overvoltages

Feeder trippings due to earth fault and over current are recorded in the Grid Substations and other MV breakdowns are recorded in the relevant Consumer Service Centers. But instances of transient disturbances resulting in momentary degradation of power quality (ex: Voltage sags and surges) were not recorded in the system and, as a result, were not analyzed in this assessment. Many disturbances and feeder trippings are caused by weather related incidents. Rain fall data in this region were studied and details are shown in the Fig. 2. 6 (Data of Welimada Estate). These data indicates that bad weather conditions were prevailed during the months of January to April and in the period of August to December.

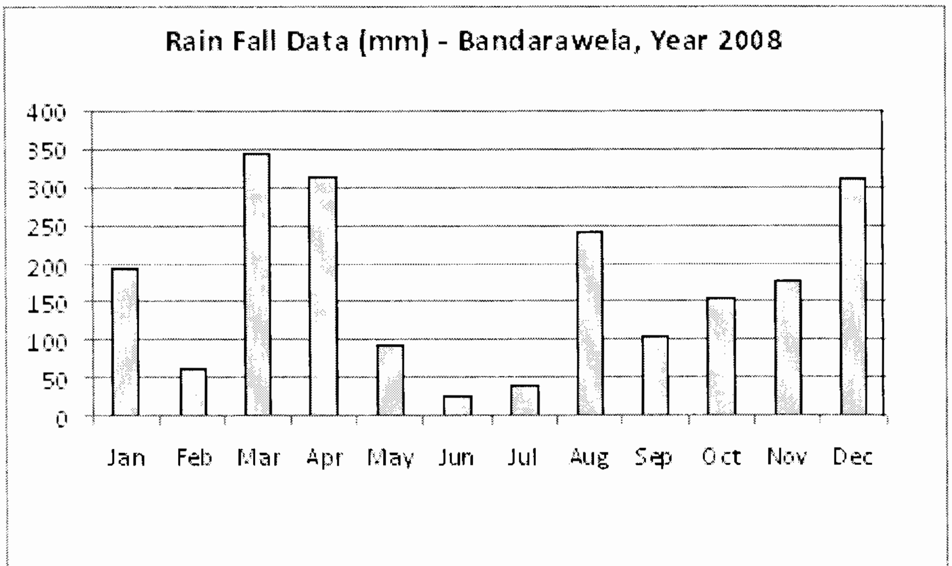

Fig. 2.6- Rainfall data in Bandarawela area, Year 2008

Details of feeder trippings in Badulla grid station due to earth fault and over current for the year 2008 is shown in the Fig. 2.7. These details reveal that some feeders have over fifty feeder failures during the rainy periods. All the feeder failures follow the same pattern in bad weather.

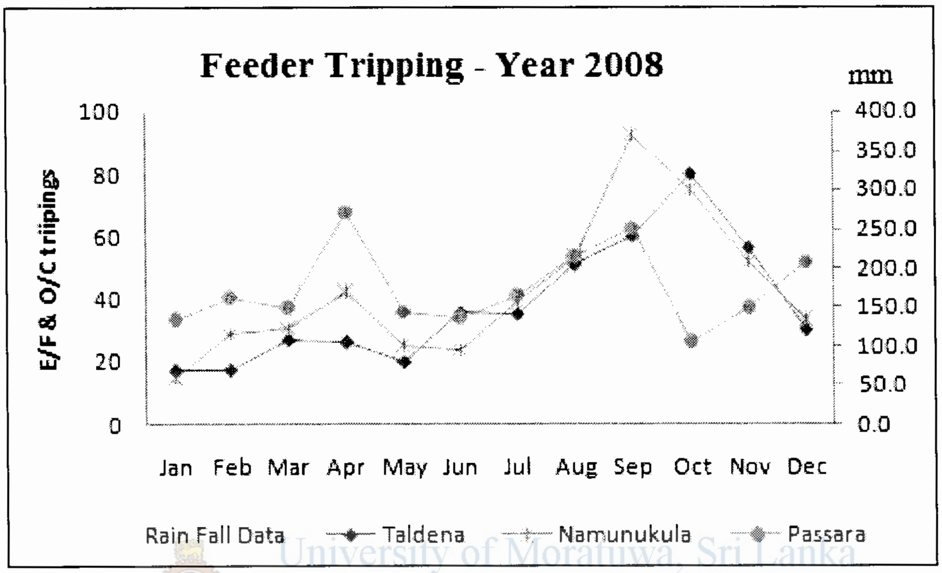

Fig. 2.7- Earth Fault and Over Current trippings

A review of past data showed each outage could be categorized as being due to one of six distinct failure initiating events:

- Way Leaves Problems
- Conductor Problems
- Insulator & Surge Arrester Failures
- Fuse Failures
- Transformer Failures
- Other Reasons

Fig. 2.8 shows the analysis of monthly MV breakdowns in the Uva province for the year 2008. A key finding of the failure analysis is that the number of fuse failures is considerably high. Also events such as transformer failures, insulator failures and fuse failures follow the same weather pattern.

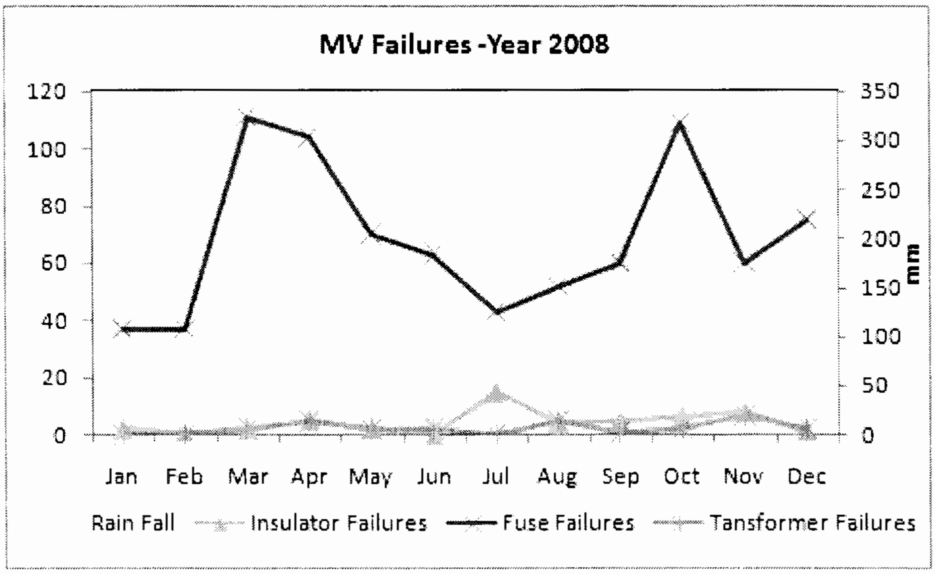

Fig. 2.8- Monthly MV failures in the Uva province.

2.4 Transient Overvoltages Related Failures

A transient can be a unidirectional impulse of either polarity or a damped oscillatory wave with the first peak occurring in either polarity. An impulsive transient is a sudden, non–power frequency change in the steady state condition of voltage, which is unidirectional in polarity and it is normally characterized by their rise and decay times. The most common cause of impulsive transient is lightning. Lightning strikes can cause momentary outages and power quality problems [2]. The mechanisms which influence the induced voltage on overhead lines from nearby lightning strokes have been reported by many researchers in the last decade.

An oscillatory transient is a sudden, non-power frequency change in the steady state condition of voltage, which includes both positive and negative values. Oscillatory transients can be originated from switching actions. The most important transient overvoltages mainly originated in a lightning stroke occurring either on the MV network side or near to LV network.

The other causes of transient overvoltages are

- Line/Cable switching (due to reflection of traveling wave)
- Capacitor bank switching (Not prominent in this region)
- Transformer energization.

- Connection/ Disconnection of loads
- Tripping of fast breakers/fuse operation [3]

Fig. 2.9 shows the total number of MV failures during the year 2008 in Uva province relevant to each major event. It reveals that 28 numbers of transformers were failed during the year 2008 and it is 2% of the total population of transformer in the province. This failure rate is much higher value than the globally accepted value of 0.5 % of the population. The main suspected reason for transformer failures is noted as lightning in failure reports. Also 51 numbers of lightning arresters and MV insulators were damaged during the year 2008 and lightning is the main causes for damages. Fig. 2.10 shows some samples of damaged insulators by flashovers or by an unknown reason.

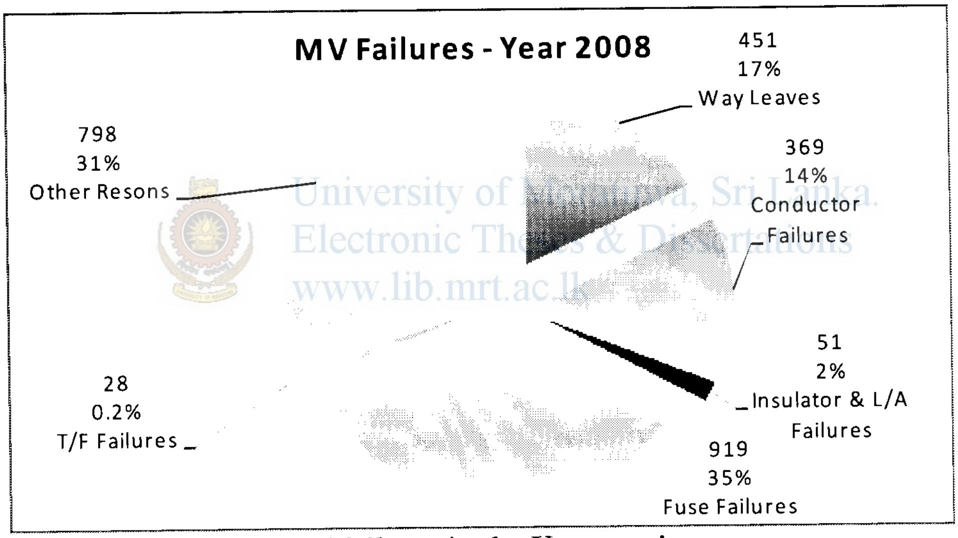

Fig. 2.9- Analysis of MV failures in the Uva province

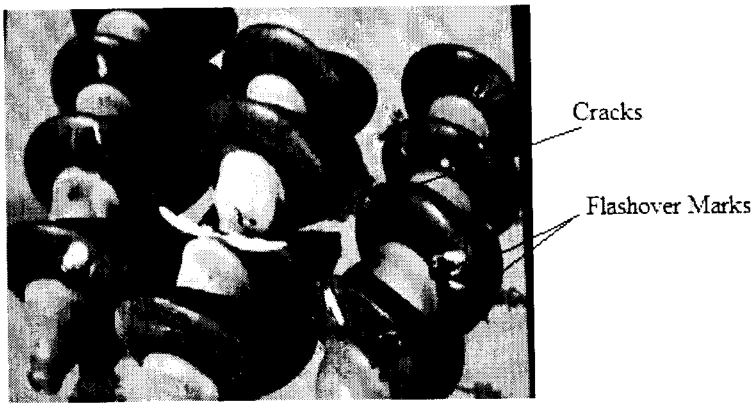

Fig. 2.10- Damaged insulators by flashovers or by unknown reasons

Since failures due to touching of way leaves or short circuiting of conductors are reported separately, the cause for recorded fuse failures can be considered as nuisance fuse blows. Data relevant to fuse usage in four consumer service centers were analyzed to study any dependency with transient overvoltages. Especially low current range of HT fuses such as 2A, 3A, 5A and 6A are used to protect distribution transformers and high current range of fuses over 6A are used to protect spur lines from its earth fault and over current faults. In the distribution sub stations in CEB network, DDLO fuses are fixed at the source side and lightning arresters are installed at the transformer side. LT fuses are also used to protect transformer from it's over current and earth faults at LT side. The distance between the DDLO fuse links and the transformer is very short; hence the chances for short circuiting or touching of way leaves are limited. Therefore, the reason for blowing of HT fuses in distribution sub station is hardly to think as O/C or E/F. Reason for this type of nuisance fuse blowing may be due to lightning. By analyzing the number of fuse usage by each CSC, it can be seen that a large number of fuses were used during the year 2008 and this amount is considerably high when compare with the total number of substations. Fig. 2.11 and Fig.2.12 shows the usage of fuses by these CSCs.

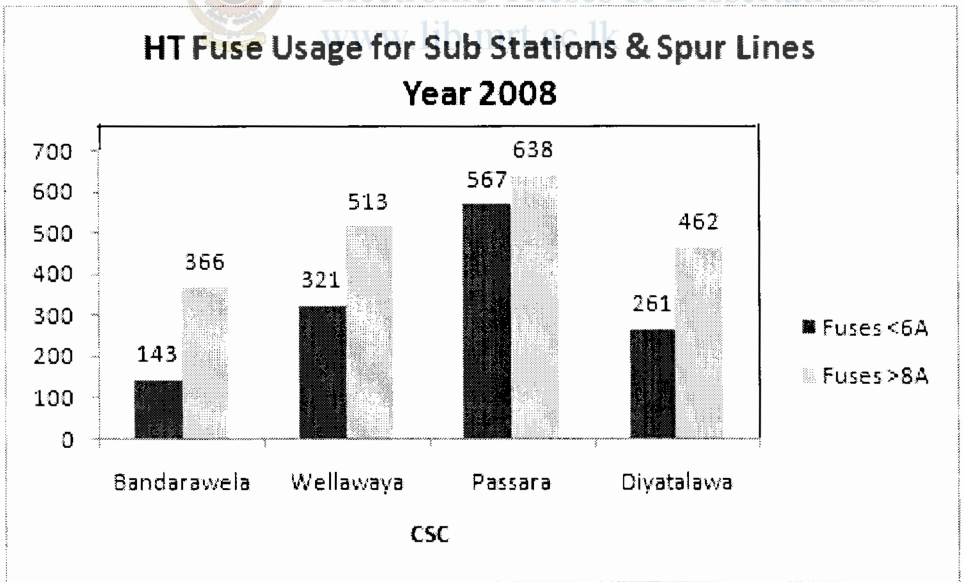

Fig. 2.11- HT fuse usage for sub stations and spur lines.

Identification of failures and damages due to transient overvoltages is not an easy task. Therefore some of the events such as transformer failures, fuse blowing (Not relevant to earth fault or over current), failure of lightning arresters and insulator failures can be considered as lightning related failures. Fig. 2.13 shows that about 37 % of lightning related failures can be observed from the total MV failures of the Uva province.

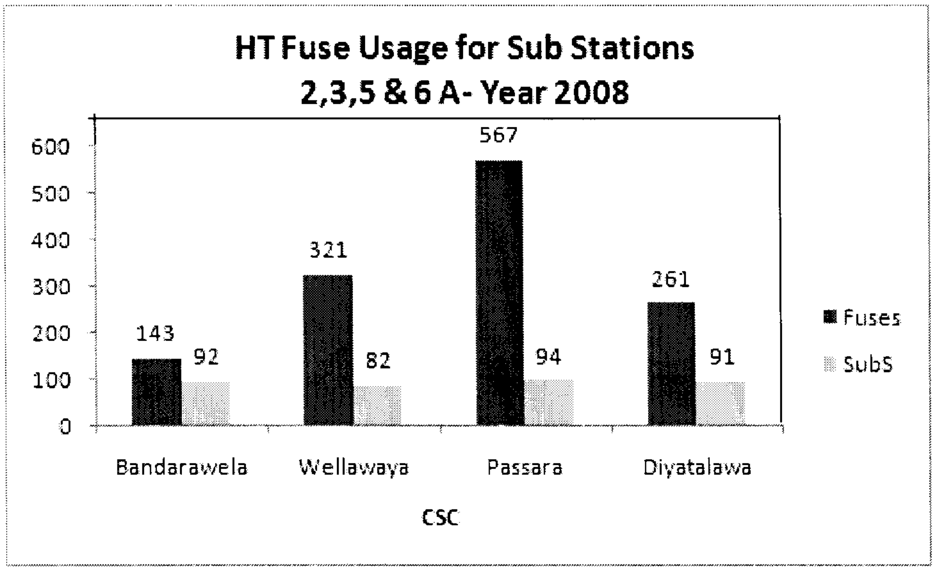

Fig. 2.12- HT fuse usage and number of sub stations .

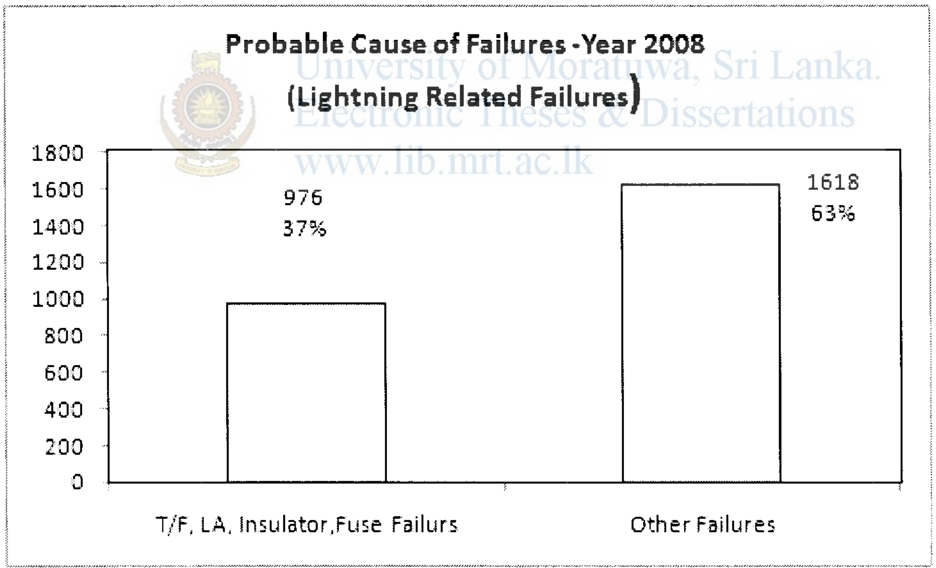

Fig. 2.13- Lightning related failures in the Uva province

A key finding of the failure analysis is that the whether related events account for over half of the feeder outages recorded. Insulation breakdown damage due to lightning is also suspected at least a dozen of the equipment failures observed. Therefore it is clear that failures due to transient overvoltages play a major impact to the reliability of MV network and hence study of transient overvoltages and mitigation measures are very important to improve the quality of power supply.

Chapter 3

Lightning Performance of Distribution Feeder Lines.

Lightning is a major source of disturbances for all electrical installations and can affect them in several manners. Even if the current is transmitted by the high-voltage lines, it can affect any electrical circuit at all voltage levels.

The effect can be

- Thermal (welding of parts, fire, explosion)
- Mechanical, due to the electrodynamic forces exerted on nearby parallel conductors.
- Dielectric shock, following increases in potential during wave propagation through the impedance of the conductors
- Insulation breakdown following flashover of a phase insulator, resulting in a follow-on-current flowing to earth at power frequency.
- Increase in earth potential [4]

Lightning is an electric discharge in the form of a spark or flash originating in a charged cloud. The formation of storm clouds, in effect of aerosols, is accompanied by electrostatic phenomena in which differently charged particles separate. The light, positively charged particles are drawn upward by ascending air currents and heavy, negatively charged particles fall under their own weight. When the limiting gradient of the breakdown voltage is reached, a discharge takes place in the cloud, between clouds or between the cloud and the earth. The latter case is called lightning. What appears as a single flash of lightning usually consists of number of successive strokes, following the same track in space, at intervals of a few hundredth of a second. The average number of strokes in a multiple stroke is four, but as many as 40 have been reported [5].

Activity of cloud- to- ground lightning flashes are higher during the monsoon thunderstorms over Sri Lanka. The Northeast monsoon produces over 884 cloud-to- ground flashes with a peak lightning rate of 96 flashes per hour whereas Southwest monsoon produces 3294 flashes with a peak rate of 104 flashes per hour. The percentage of positive flashes and average peak lightning current values for negative flashes are found to be 6.4% and 36 kA [15]. Geometry of lightning leader and its effect to the distribution lines is explained in the Fig. 3.1.

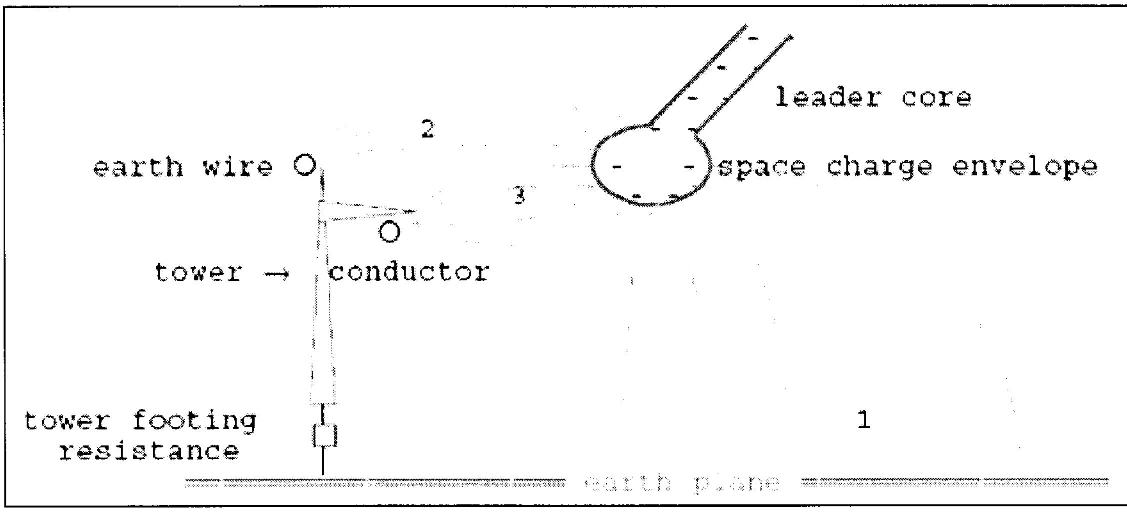

Fig. 3.1- Geometry of lightning leader and transmission line

There are three possible discharge paths that can cause surges on the line.

a- Induced voltage due to a lightning stroke to nearby ground.

In the first discharge path 1 (Fig 3.1), which is from the leader core of the lightning strikes to the earth, the capacitance between the leader earth is discharged promptly, and the capacitances from the leader head to the earth wire and the phase conductor are discharged ultimately by traveling wave action, so that a voltage is developed across the insulator strings.

b- Back-flashover mode or Indirect strike

The second discharge path (2) is between lightning lead and the earth conductor. It discharges the capacitance between these two. The resulting traveling wave comes down the tower and, acting through is effective impedance, raise the potential of the tower top to a point where the difference in voltage across the insulation is sufficient to cause flashover from the tower back to the conductor.

c- Shielding failure or direct strike

The third mode of discharge (3) is between the leader core and the phase conductor. This discharges the capacitance between these two and injects the main discharge current into the phase conductor, so developing a surge impedance voltage across the insulator string.

At relatively low current, the insulation strength is exceeded and the discharge path is completed to earth via the tower. [5]

Knowledge of the frequency of occurrence of lightning strokes is utmost importance to decide the lightning performance in distribution lines. The keraunic level is defined as the number of days in the year on which thunder is heard. It has been found by experience that the keraunic level is linearly related to the number of flashes per unit area per year. In most areas of the world, an indication of lightning activity may be obtained from keraunic data (Thunder days per year). The keraunic level is an indication of regional lightning activity based on average quantities derived from historically available ground level observation.

The reliability of a distribution line is dependent on its exposure to lightning. Therefore, a key lightning incidence parameter is the average number of flashes to earth per square kilometer, per year along the line corridor. This parameter, called the ground flash density (GFD), is determined by averaging years of ground flash counts recorded by locating systems.

Ground flash density (GFD) may be estimated from the isokeraunic level using equation

$N_g = 0.04\ T_d^{1.25}$ [flashes/km2/yr]

Where

T_d is the number of thunder days per year (Isokeraunic level) [6]

Data of Average Thunder Days per year and Ground Flash Density in areas such as Badulla, Bandarawela and Hambanthota is given in the Table 3.1. Lightning incidence parameters in areas such as Wellawaya, Buttala and Thanamalwila are considered as same as in Hamabnthota area.

Meteorological Station	**Average Thunder Days T_d**	**Ground Flash Density Ng**
Badulla	91	11.24
Bandarawela	114	14.9
Hambanthota	52	5.59

Table 3.1- Thunder Days and GFD in Uva province

The magnitude of a current impulse due to a lightning discharge is a probability function. For the sake of handling the probabilistic distribution of current peak values in a simple way, the following expression is adopted [6].

$$P(Ip>=Ip^*) = \frac{1}{1+(Ip^*/31)^{2.6}}$$

This equation is used to calculate the probability for lightning peak current Ip to be equal or greater than a given value Ip* [kA] and resultant probability values are given in the Table 3.2. Low discharge levels up to 10kA may result in a higher tendency for the lightning strike to pass by any shield wire.

Ip[KA]	Probability (Ip>Ip*)
2	0.999
5	0.991
10	0.75
31	0.5
50	0.224
70	0.107
100	0.045
200	0.014

Table 3.2- Probabilistic distribution of current peak values

Lightning causes a significant part of the disturbances, damages and unscheduled supply interruptions in the modern power systems. This is the reason why over the last years, many lightning performance estimation procedures have been presented in different technical literatures. Methods for determining the lightning performance of high voltage distribution lines considers both, shielding failures (Direct strokes), where the lightning stroke terminates directly on the phase conductors and backflashover rates, where the lightning stroke terminate on structure or shield wire. Also induced voltage from nearby strokes may affect the lightning performances of distribution lines.

3.1 Direct Lightning Strikes on Phase Conductors

The flash collection rate N, in open ground (No significant trees or building nearby), is estimated by Eriksson's equation. [6]

$$N = N_g \left(\frac{28h^{0.6} + b}{10} \right)$$

Where h = pole height, m

b = structure width, m

N = flashes/100km/year

Ng = ground flash density, flashes/km2/year

The exposure of the distribution line to lightning depends on how much the structures protrude above the surrounding terrain. Structures located along the top of mountains, ridges, or hills which are more predominant in this province will be more likely targets for lightning strikes than those shielded by natural features. Trees and building may intercept many lightning flashes which otherwise would have hit a line.

The shielding factor, S_f is defined as the per unit portion of the distribution line shielded by nearby objects.

The Number of strikes per 100 km line length is then [6]

$$N_s = N\,(1-S_f)$$

By taking reasonable value for S_f as 0.5 calculated values of number of strikes to a line (100 km length) is shown in the Table 3.3. Where pole height h was considered as 9.2 m and line width b was considered as 2.2m. Height of tower line h was considered as 14 m and line width b was considered as 3m.

Shield wire is placed above the phase wires in tower lines. Therefore all flashes to the distribution line are assumed to strike the shield wire. The number of flashovers reduced by the shield wire may be determined from the graph given by IEEE guide (Fig. 3.2) [6]. The average ground resistance can be taken as 40 ohms (Appendix B.4), BIL can be considered as 350 kV for tower lines. Then 35 % of reduction in direct hits can be achieved by the shield wire in tower lines.

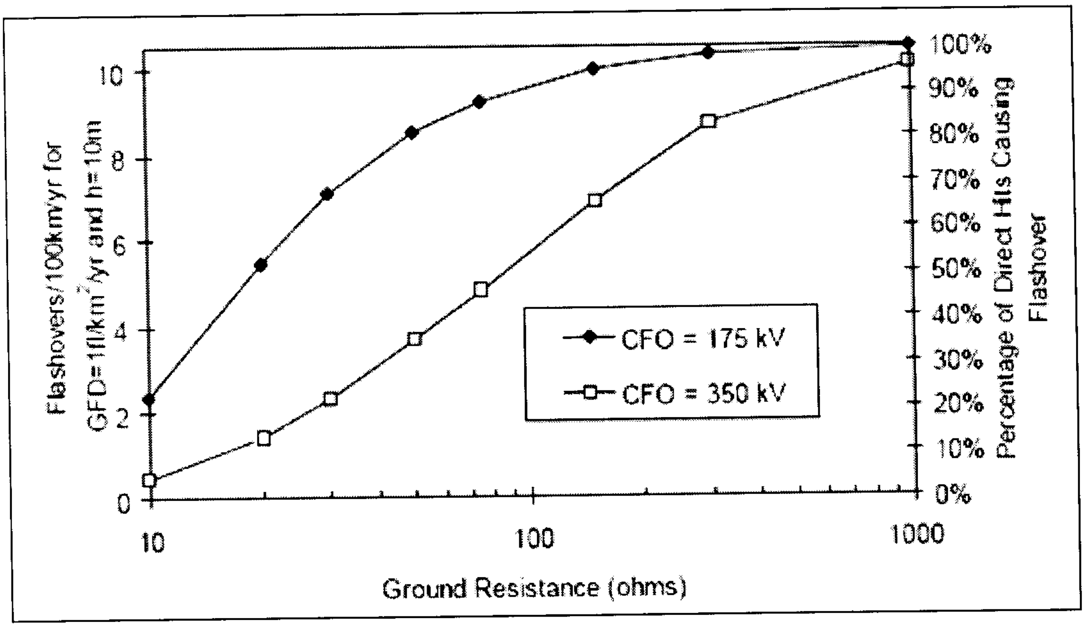

Fig. 3.2- Effect of grounding resistance on shield wire performance

		Pole Line		Tower Line		
Td	**Ng**	**N**	**Ns**	**N**	**Ns**	**Ns 35%**
52	5.6	60.4	30.2	77.8	38.9	13.6
91	11.2	121.6	60.8	156.5	78.2	27.4
114	14.9	161.2	80.6	207.4	103.7	36.7

Table 3.3- Number of direct flashes per 100 km length

The overhead shield wire in tower lines reduces its direct hits by 35%. Therefore, these data reveals that although pole lines are lower than tower lines (But not considerably) number of direct flashes are higher. This variation is illustrated in the Fig. 3.3 for different thunder days. Higher flashover rates can be experienced in areas with high flashover density. Since these lines are spread over different geographical areas having different ground flash densities, flashover rate has to be calculated considering values of tower and pole line lengths and their GFD values. Pole line length is 72 % of its total length of the Namunukula feeder; hence the contribution for flashovers is high.

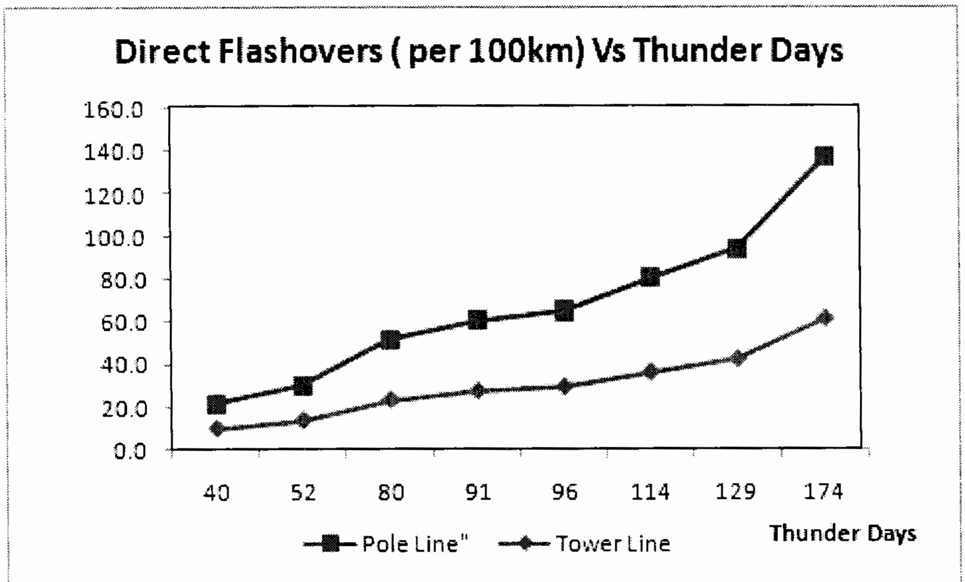

Fig. 3.3- Comparision of direct flashover rate for tower and pole line

Most of the feeder lines are combined with tower and pole lines and covers different geographical areas having different isokeraunic levels. Thunder days relavant to Feeder 1 is considered as same as in Badulla area. Feeder 2 and Feeder 3 can be considered as in the isokeraunic levels at Banadarawela area. But in feeder 5, it can be considered as 40 % of it's length is in isokeraunic levels of Badulla, 40% in Bandarawla isokeraunic levels of Bandarawela and 20% in Hambanthota isokeraunic levels. Feeder 5 also can be considered as 70 % of it's length is in Badulla isokeraunic levels and 30% in in Hambanthota isokeraunic levels. Therefore, according to above line proportions, number of direct strikes per year can be calculated for feeder lines as in the Table 3.4.

Feeder	Feeder Name	Total Length km	Tower Line km	Pole Line km	Direct Flashes/Year
F1	Taldena	288	72	216	151.06
F2	Bandarawela Old	71	17	54	49.7
F3	Bandarawela B/B	129	97	32	61
F4	Badulla Town	11	0	11	6.69
F5	Namunukula	274	76	198	145.34
F6	Passara	499	124	375	222.4

Table 3.4- Number of direct stokes per year

3.2 Induced Voltage Flashovers

Lightning strike may also strike in the vicinity of an overhead line without directly striking the line, shield wire or the structure itself. If this creates high enough voltages in the phase conductors, this could cause a flashover of the insulation. Induced voltage flashover frequency may dramatically increase for low level insulation.

Fig. 3.4 illustrates the frequency of flashover as a function of the critical flashover (CFO) voltage of the line [6].

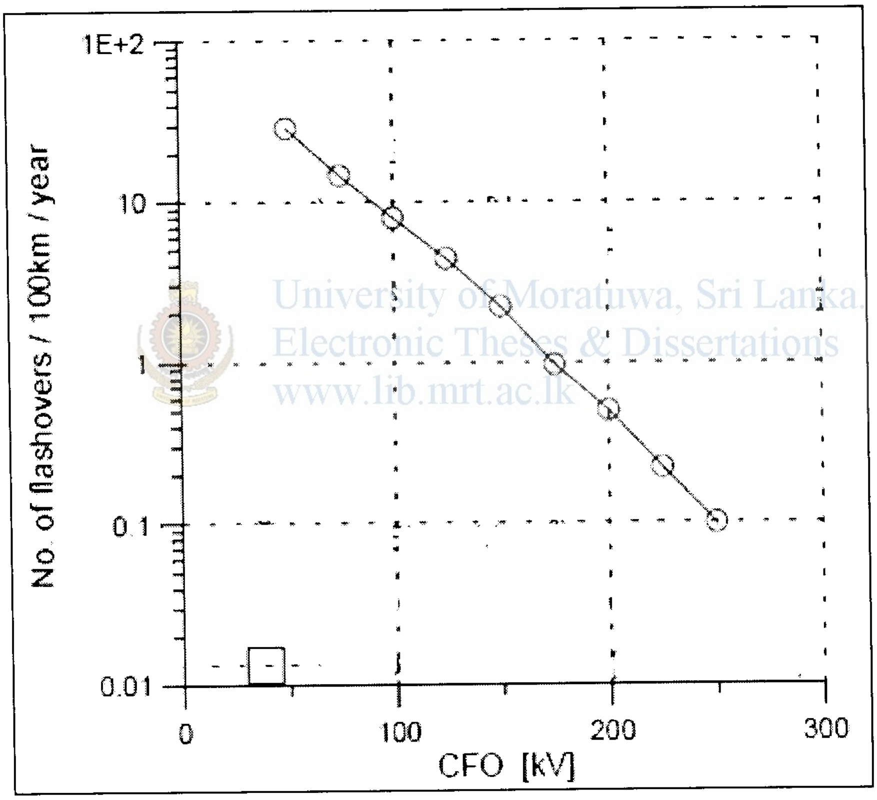

Fig. 3.4- Number of induced flashovers versus distribution line insulation level

The values are normalized for a GFD of 1 flash/km2/yr and a distribution line of height of 10m.

Considering BIL level in pole line as 200kV and 300 kV in tower line, number of induced flashovers in open ground may be estimated from Figure 3.4. Therefore, estimated value of induced flashovers per 100 km length is shown in the Table 3.5.

BIL(kV)	Flashovers/100km/Year		
	Td 52	Td 91	Td 114
200	2.795	5.62	7.45
300	0.168	0.337	0.447

Table 3.5- Induced flashovers per 100 km

With these values, number of induced flashovers in feeder lines per year can be calculated as in the Table 3.6.

Feeder	Feeder Name	Total Length km	Tower Length km	Pole Length km	Induced Flashes/ Year
F1	Taldena	288	72	216	16.41
F2	Bandarawela Old	71	17	54	3.09
F3	Bandarawela Back Bone	129	97	32	2.13
F4	Badulla Town	11	0	11	0.62
F5	Namunukula	274	76	198	11.72
F6	Passara	499	124	375	22.52

Table 3.6- Number of Induced flashes per year

Number of induced flashovers per year is very less compared to the number of direct flashes of a feeder line. Lengthy lines are experienced more induced flashovers. Since pole lines are having less insulation level, more flashovers can be observed in feeder line which has lengthier spur lines.

These values are given for a distribution line in open ground with no nearby trees or buildings. The number of flashovers depends on the presence of nearby objects which may shield the line from direct stroke. This may increase the induced voltage flashovers because there are more nearby strokes.

Given the random nature of lightning, any calculation has to be kept within probabilistic bases. Therefore, for the evaluation of the lightning-induced voltages, simplified formula derived by Rusck formula can be adopted. It gives the maximum value V_{max} (in kV) of the induced overvoltages at the point of the line nearest the stroke location.

The maximum voltage that is induced in a power line in the point closet to the strike is given by [6]:

$$V_{max} = \frac{Z_0 . I_p . h}{d}\left[1 + \frac{1}{\sqrt{2}} . v . 1/\sqrt{(1 - 0.5v2)}\right] \qquad (1)$$

Where $Z_0 = \frac{1}{4\pi} \sqrt{\mu o / \epsilon o} = 30\Omega$

In which I_p is expressed in kA, h- height of the line is expressed in m, d- distance of the stroke location from the line center is expressed in m, and v is the ratio between the return-stroke velocity and velocity of the light.

The value v can be taken as 0.4

If the distance of the stroke location from the line is beyond the so called lateral distance d_l, the event is considered as an indirect flash and maximum amplitude of the induced voltage is computed, otherwise it is considered a direct flash.

The Lateral Distance d_l can be explained as

$$d_l(I_p) = \sqrt{r_s^2 - (0.9. r_s . h)^2}$$

with $r_s = 10.I_p^{0.65}$

Where I_p is the amplitude of the lightning current, r_s is the striking distance to the conductor and h is the conductor.

The amplitude of the stroke current is varied from 1 to 200 kA in intervals of 1 kA. The number of annual insulation flashovers per km of distribution line F_p is obtained as the summation of the contributions from all intervals considered

$$F_p = 2 \sum_{i=1}^{200} (d.max - d.min).N_g.P_i \qquad (2)$$

Where P_i is the probability of current peak I_p to be within interval 1 to 200 kA, $d_{.min}$ (i.e. lateral distance) is the minimum distance for which lightning will not divert to the line, $d_{.max}$ is the maximum distance at which the stroke may produce an insulation flashover.

The maximum distance $d_{.max}$ for every peak current interval is then calculated.

Vmax= 1.5*CFO

Ng = flashes/km^2/yr

Example

Considering a 33kv, 9.2 high pole line having 200 kV BIL, with a flash density of 11.4 flashes/km2.

Striking distance for 100 kA surge current

$r_s = 10.I_p^{0.65}$

$= 199.5$ m

Then lateral distance $d_l(I_p) = \sqrt{r_s^2-(0.9.\ r_s-h)^2}$

$= \sqrt{199.5^2-(0.9x199.5-9.2)^2}$

$= 103.8$ m

Then Vmax = 1.5x CFO

= 300 kV

Substituting these values in equation (1), maximum distance d_{max} can be calculated as

$d_{max} = 30 \text{ x } 100 \text{ x } 9.2 \text{ x } (1 + 0.707 \text{ x } 0.4 \text{ x } 1/(\sqrt{(1-0.5x0.4^2)})) / 300$

$= 120.28$ m

In open ground, the three following scenarios may occur:

a) If the stroke comes down between d =0 and lateral distance d_l = 103.8 m, the stroke will hit the line.(i.e., direct stroke)

b) If the stroke comes down between d_l and d_{max} = 120.28 m, the stroke will hit the ground and cause an induced voltage flashover.

c) Beyond d_{max} = 120.28 m, the stroke will hit the ground and not cause a flashover.

From Table 3.2, probability exceeding 100 kA surge current is 0.045.

Therefore substituting these values in equation (2), and for GFD value of 11.4 flashes/km^2, we can calculate number of induced flashes per km as

2 x 0.045 x 11.4 x (120.28-103.8)/1000

0.0148 flashes/km

Finally, the number of insulation flashovers per km of distribution line and per year, F_p, is obtained as the summation of the contribution from all surge current intervals as expressed by equation (2).

3.3 Total Number of Flashovers (Lightning Performance)

The performance of a line expressed as the annual number of lightning flashovers on a circuit [6].

The total number of annual insulation flashovers
= Direct strokes + Induce voltages flashes

Lightning performance of each feeder line is shown in the Fig.3.5.

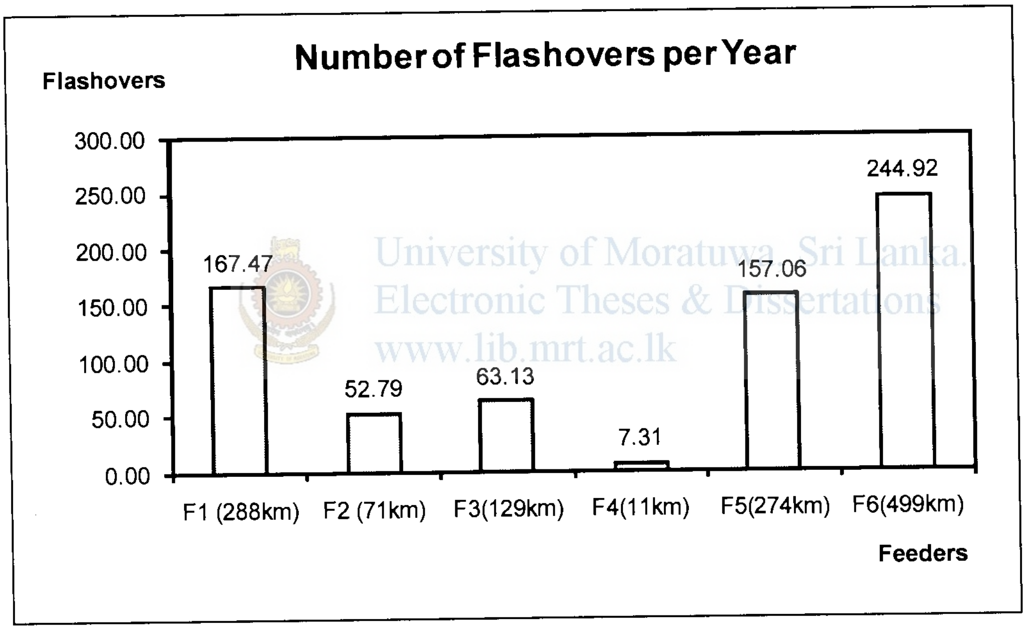

Fig. 3.5- Total flashovers (Lightning Performance) of feeders

Data reveals that feeder lines having more line length, running over high ground flash density areas and having more spur lines are subjected to more flashovers.
Feeder 6 (Passara Feeder) shows the most poor performance and having more flashes.

More than eight flashovers may be required to damage the surface of insulators [3]. Insulator sets with surface damages were changed during the maintenance program of year 2008 and details of those replaced insulators are shown in the Fig. 3.6. This figure shows that numbers of damaged insulator sets are high in less performing feeders.

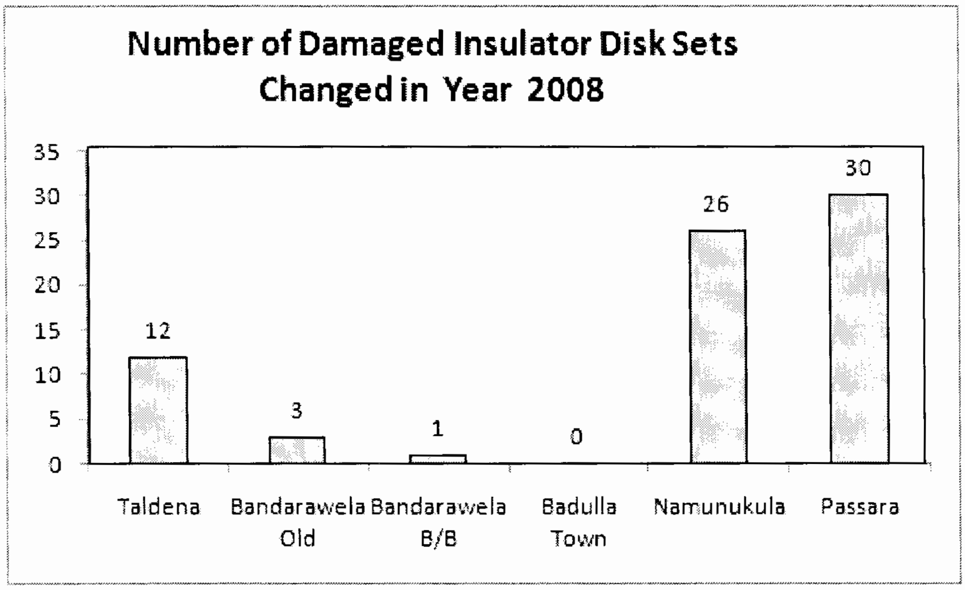

Fig. 3.6- Number of damaged insulator sets changed in year 2008

3.4 Study of Shielding Effect from Nearby Trees

Trees and buildings may play a major role in the lightning performance of distribution lines. Since pole lines are less high (9.2m), it is assumed that nearby trees and buildings may intercept many lightning flashes which would have hit on the line. Considering practical difficulties and economical reasons (Pole must be high enough to support the shield wire and more failures are experienced due to broken earth wire), shield wire is designed to fix under phase wires in pole lines to reduce damages due to induced flashovers.

An electrogeometric model may be used to estimate the shielding factor for a specific portion of a distribution line. An electrogeometric model is based on the idea that a distribution line or other object has a certain attractive radius which increases with height and magnitude of the lightning flash. Fig. 3.7 illustrates natural shielding effect from nearby tress.

Where, R_S is the striking distance relevant to that surge current ($Rs = 10.I_0^{0.65}$).

Rg is the striking distance to the ground and can be expressed as Rg = 0.9 Rs [6].

If the tree is higher than the pole line and nearby enough then the striking distance curve of the tree covers the phase wires. This figure shows that right side phase of the pole line is shielded by the nearby tree for that particular lightning current

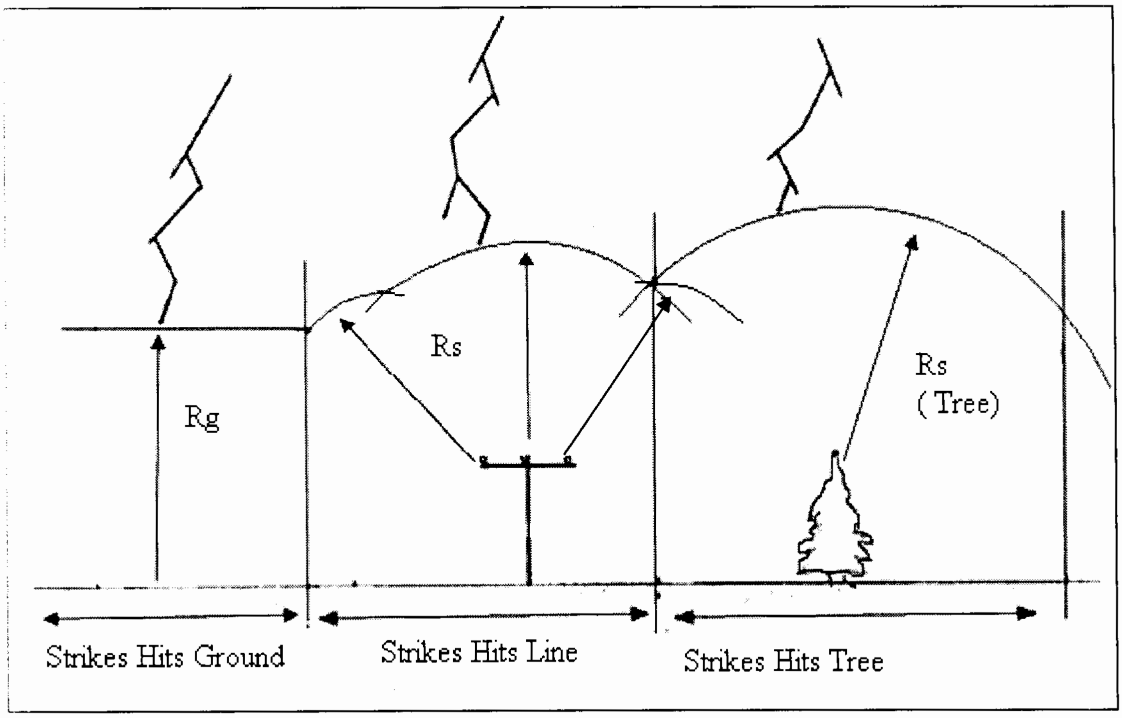

Fig. 3.7- Shielding effect from nearby trees

Fig. 3.8 illustrates the means for approximating the shielding factors for objects of various heights. These values are based on a 10 m tall distribution line. This diagram shows that over 10m high tree must be there at a distance of 10m from the distribution line to have shielding factors over 0.5 [6].

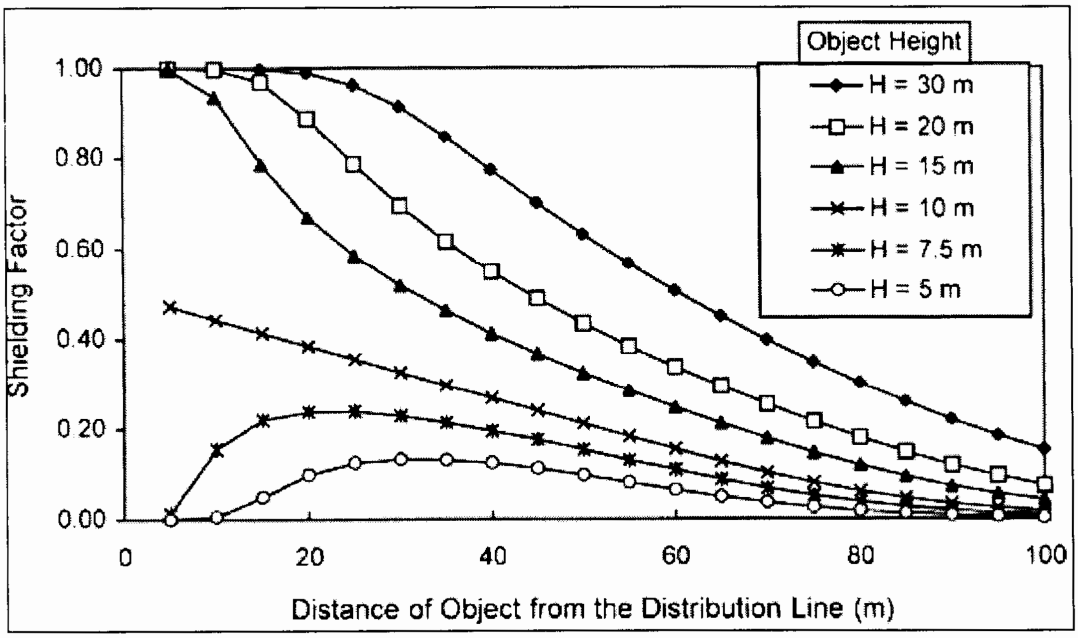

Fig. 3.8- Shielding factors due to nearby objects

A shielding factor 0.0 means the distribution line is in the open ground with no shielding by nearby objects provided, and a factor of 1.0 means the distribution line is completely shielded from direct strikes.

Different pole lines were examined to check the shielding effect from nearby trees by noting down distances from line to trees which are over 10m high.

Details are given in the Table 3.7.

Spur Line	Span	Left side m	Right Side m	Spur Line	Span	Left side m	Right Side m
Kudaoya-Debarawawa	1 (70m)	14	16	New Burg Sub	1 (70m)	>10m	>10m
	2 (70m)	12	18		2(70m)	>10m	>10m
	3(70m)	10	20		3(70m)	>10m	>10m
	4(70m)	20	12		4(70m)	<10m	<10m
	5(70m)	15	13				
	6(70m)	18	15	Ballaketuwa Sub	1 (150m)	>10m	>10m
					2(70m)	>10m	>10m
Kumbalwela Sub	1 (70m)	<10m	<10m		3(70m)	>10m	>10m
	2(70m)	>10m	>10m		4 (70m)	>10m	>10m
	3(70m)	>10m	>10m				
	4(70m)	>10m	>10m	Namunukula Town	1 (200m)	>10m	>10m
	5(70m)	>10m	>10m		2 (50m)	>10m	>10m
	6(70m)	>10m	>10m		3 (70m)	>10m	>10m
	7(70m)	<10m	<10m				
	8(70m)	<10m	<10m	Passara	1 (300m)	>10m	>10m
	9(70m)	>10m	>10m		2 (200m)	>10m	>10m

Table 3.7- Distances for nearby trees

Data reveals that over 10 m tall trees are not close enough to protect lines from direct strikes. Therefore, the shielding factor can be considered as less than 0.5 in these particular lines. These types of feeder lines which are installed on high ridges or on top of hills are very common in this province. In most cases this type of spur lines are used to connect tower lines making them vulnerable to lightning. Unless distribution line is protected with a shield wire or arrester, all direct lightning flashes will cause flashovers regardless of insulation level, conductor spacing or grounding [6].

3.5 Determination of Critical Flashover Voltage (CFO) for Possible Flashover Paths.

The more common insulating components used in overhead distribution line construction are porcelain, air, wood, and fiberglass. Each element has its own insulation strength. The CFO is defined as the voltage level at which statistically there is 50% chance of flashover and a 50% chance of withstand. When the insulating materials are used in series, the resulting insulation level is not the summation of those levels associated with the individual components, but is something less than that value. The extended CFO added method may be used to estimate the total CFO of a distribution structure by [6]:

$$\mathbf{CFO_T = CFO_{ins} + CFO_{add.sec}}$$

Where CFO_{ins} is the CFO of the primary component

$CFO_{add.sec}$ is the CFO added by the second component

Estimated values of CFO voltages for different flashover paths are shown in the Table3.8.

Type	From	To	Flashover path	Added CFO (kV)	Total CFO (kV)
Tower/ Lattice pole	GW	PW	Insulators (3Discks)	320	320
	PW	GW	Insulators (3Discks)	320	320
Pole (Wooden)	PW	GW	Pin insulator + Earth wire	180	180
			Pin insulator + Pole (without earthing)	180 + 2350	2530
			Pin Insulator + Stay wire	180 + 30	210
			Tension Insulators + Earth Wire	320	320
			Phase wire to EW through air	300	300
Pole (Concrete)	PW	GW	Pin insulator + Earth wire	180	180
			Pin insulator + Pole	180	180
			Pin Insulator + Stay	180 + 30	210

Table 3.8- Critical Flashover Voltage values for possible flashover paths.

The cross arm assembly is grounded in pole lines. Therefore the lowest CFO level for flashover path is found for flashovers from phase wires to earth wire through pin insulators in pole lines (180kV). Since the stay wire insulators are having least BIL value (30 kV), the next flashover path having lowest CFO value is flashover through pin insulator to stay wire.

3.6 Testing of Insulators to Check Deterioration of Insulation with Aging.

The reliability of supply provided by an electric power system, as judged by the frequency and duration of supply interruptions to customers, depends to a great extent on the surge performance of the system. Although there are many other causes for interruptions, breakdown of insulation is one of the most frequent. Flashovers of contaminated insulators, in general, occur during weather conditions that permit the pollution layer to be moistened by rain, fog or light misty rain. A lighting flashover resulting in a sustained power follow will lead to an outage. The pollution may reduce the power frequency flashover voltage of porcelain insulation to half or even to a quarter. The withstand voltage of switching impulses is approximately twice the level of the power frequency withstand voltage for the same pollution level. The main factors affecting the pollution flashover of insulators are, namely, the applied voltage, severity of deposited pollutant, thickness of pollution and humidity [8]. Severity of the flashover and consequent of flashovers may damage the surface glazing of the insulator and some time may crack the insulator. It is the practice that significantly damaged insulators are replaced in maintenance programmes. Washing of contaminated insulators is very time consuming and costly, hence it is a rare practice used in maintenance.

Therefore to identify the severity of deterioration of insulation levels in insulators, impulse test and power frequency flashover tests (Dry and Wet condition) were carried for sample of insulators having different amount of surface flashovers. Insulator set covered with moss and dust was also tested. Area of surface flashover in damaged insulators was measured and presented as a percentage of total surfaces of the insulator. Most samples were not shown flashovers even for maximum voltage applied. Therefore the flashover voltage can be considered above the maximum applied voltage in those cases.

Details of measured data are given in the Appendix B.5.

Typically on porcelain insulators that have flashed over there is a lot of glaze damage. Data reveals that most of the surface damaged insulators are within the designed BIL, but insulators covered with moss shows less insulation level. Thickness and severity of deposited pollutant may increase with the aging of the feeder line. Fig. 3.9 shows that most of the feeder lines in Badulla CSC are over 10 years old. As the age of the line increases, deposited amount of moss and dirt increases. Hence reduces the insulation level. Therefore washing of insulators in maintenance programmes may improve the line performances significantly. Fig 3.10 shows a sample of insulator covered with moss.

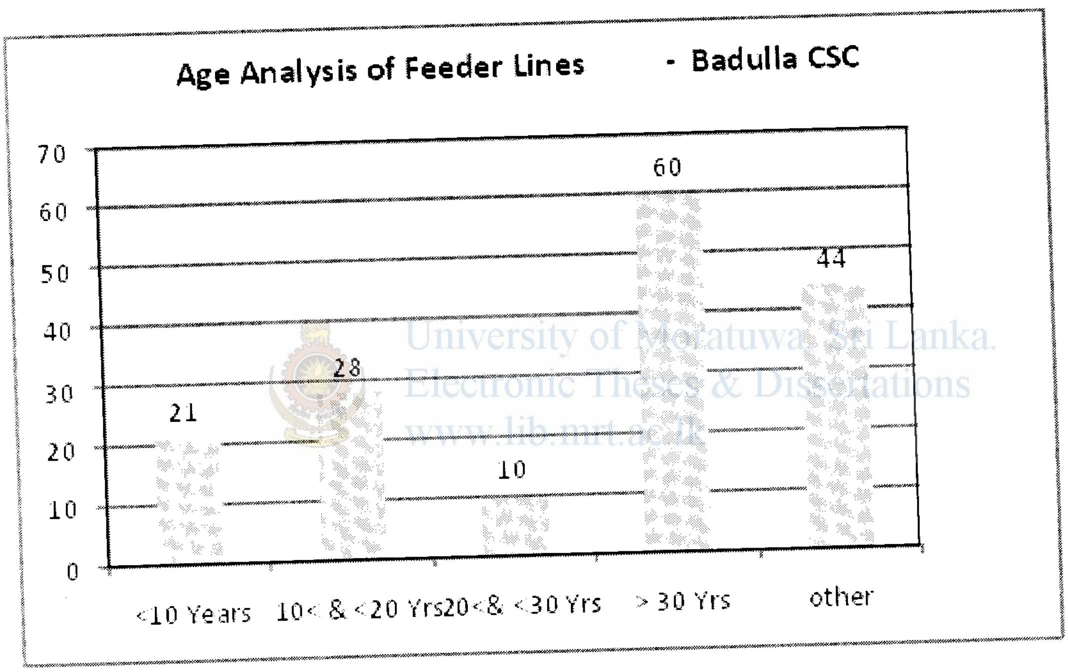

Fig. 3.9- Age analysis of feeder lines

Fig. 3.10 – Insulator covered with moss

Chapter 4

Transient Overvoltage Stress in Distribution Substations

The MV/LV substation takes major part in electric power distribution system. High reliability of system requires knowledge of the propagation of surges in major points of it. Distribution transformers may fail for a variety of reasons. Lightning surges continue to be the major cause of premature transformer failures. Fast rise time surges that generate excessive voltage through the primary arrester and connecting leads may affect the surge performance of distribution transformers.

4.1 Calculation of Impulse Resistance

Earth resistance of substations, earth rod resistance of pole line and soil resistivity was measured in different geographical areas. Relevant data is attached in the Appendix B.4.

Measured values of soil resistivity vary from 17 ohm-m (Low altitude area) to high values such as 792 ohms- m in high altitude areas. Average value of earth rod resistance in substations was found as around 45 ohms, but high values as 90 ohms were also observed. Average value of earth rod resistance in pole lines was observed as 40 ohms and high values as 260 ohms were also found. Because of considerable lightning current rise (to 100 KA/μs), the effectiveness of earthing system is often determined by inductive voltage drop [14].

Impulse resistance of an earth electrode is much less than the normal power frequency resistance (i.e. Measured or calculated resistance). This is due to the ionization and partial discharge taking place at high current densities when the lightning surges flow through the earth electrode to the surrounding earth.

Therefore Impulse resistance is given as

$$R_T = \frac{Rg}{\sqrt{1+\frac{I}{Ig}}} \qquad (3)$$

Where R_T is the Impulse resistance (Transient resistance)

R_g is earth resistance at low current and low frequency (ohm)

I is surge current into ground (kA)

I_g is limiting current initiating soil ionization (kA)

$$I_g = \frac{1}{2\pi} \bullet \frac{E_o \rho}{R_g^2} \quad (4)$$

Where ρ is soil resistivity (Ω-m)

E_o is soil ionization gradient (about 300 kV/m) [7]

Example

Calculation of impulse resistance for measured value of earth rod resistance = 40 ohms, soil resistivity = 100 ohm-m and for 10 kA surge current;

From equation (4),

$Ig = (1/2\pi)x((300x100)/40^2)$

$= 2.98$ kA

Substituting in equation (3),

Impulse resistance can be calculated as

$R_T = 40/\sqrt{1+(10/2.98)}$

$= 19.18\ \Omega$

Considering soil resistivity as 100 Ω-m, calculated impulse resistance for different lightning peak current is shown in the Table 4.1. These data shows that with the increase of surge current, impulse resistance decreases.

I [kA]	Impulse Resistance -Ohm						
	Rg=10 ohm	Rg=20 ohm	Rg=30 ohm	Rg=40 ohm	Rg=50 ohm	Rg=100 ohm	Rg=200 ohm
1	9.02	14.43	17.11	18.48	19.23	20.40	20.72
10	9.09	14.75	17.66	19.18	20.02	21.35	21.72
30	7.84	10.67	11.63	12.03	12.23	12.52	12.59
70	6.37	7.63	7.96	8.09	8.15	8.23	8.25
100	5.68	6.53	6.73	6.81	6.84	6.89	6.91
200	4.39	4.75	4.82	4.85	4.86	4.88	4.88

Table 4.1- Impulse resistance variation with lightning current

4.2 Calculation of Arrester Lead Length

Arrester lead length can be defined as any section of the arrester leads that are electrically in parallel with protected insulation and conduct impulse current during the lightning strike. Arrester lead length becomes critical during a lightning discharge because the arrester impedance becomes extremely low. The current through the lead generates a voltage due to the wire inductance and the rate-of-rise of the current.

The inductive voltage drop in lead wire carrying surge current is a function of lead wire inductance.

L (Typically 0.4 μH/ ft)

Then voltage across lead length

$V_l = L \frac{di}{dt}$

The lead voltage drop V_l is in series with the arrester discharge voltage (V_{arr}) and voltage across the earth rod resistance [10].

Case Study

Three common construction practices were identified in the system and are shown in the Fig. 4.1 as Case1, Case2 and Case 3. Two separate earthing circuits are used in substation construction. One earth electrode is used to ground the transformer neutral. Another earth electrode is used to connect surge arrester, transformer tank, cross arms and line earth wire. But different practices were observed in grounding of transformer tank. Most common practice is connecting the tank with a separate earth wire to the second earth electrode. Connecting of tank earth directly to the line earth lead was also observed.

Case 1

This is the most common practice and arrester is mounted on the transformer tank. Transformer tank earth is connected parallel to the arrester earth. Surge current pass through points A,B and C to the ground. In this system, lead length can be taken as zero.

Case 2

Due to some practical difficulties, HT cables are connected directly to the transformer HT bushing and then to the arrester. Earth connection is same as in case 1. Surge current passes through A, D, B and C to the earth. Lead length can be considered as the distance between B and D and average value is about 0.5m.

Case 3

HT connection is same as in the case 1. But in this system, earth wire is connected only to the arrester bottom and transformer tank is not grounded. Surge current passes through A,B and C to the ground. But lead length can be considered as the distance between B and C. This value can be considered as 6m in this case.

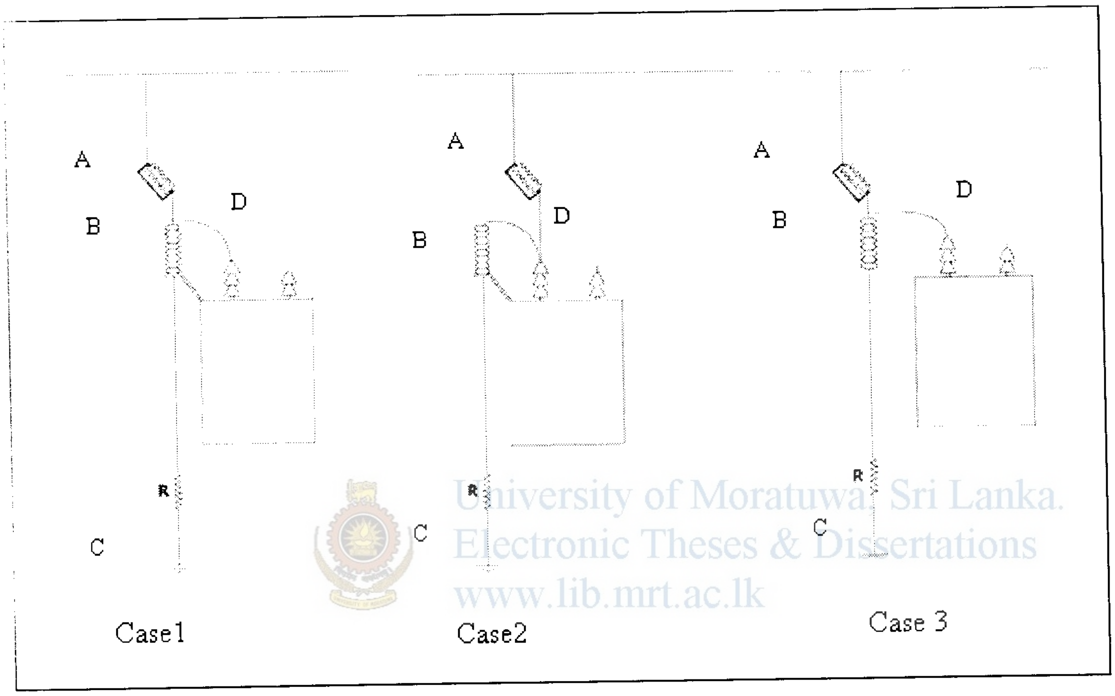

Fig. 4.1- Common practices in substation construction

In this case, for 3 KA, 1.2/50 μs surge current

$\frac{di}{dt}$ = 3/1.2 = 2.5 kA/ μs

Then the voltage across the lead length,

$L\frac{di}{dt}$ = 0.4x 19.7x 2.5 = 19.7 kV

Impulse resistance for measured value of 20 ohms can be considered as 18 ohms at 3 kA surge.

Therefore voltage across the earth rod is

I.R = 3 x 18 = 54 kV

If we take the voltage across the arrester V_{arr} as 104 kV,

Then the total voltage stress at the transformer HT Bushing is

$IR + L\frac{di}{dt} + V_{arr}$ = 54 + 19.7 + 104 = 177.7 kV.

But, transformer BIL level is 200 kV. Therefore, even at a very low range of surge currents, distribution transformer is at a risk for insulation failure.

Total voltage stress at HT bushing was calculated for each case and the results are given in the Table 4.2.

	Surge Voltage Stress kV					
Surge kA	3	10	30	70	100	200
Case 1 (kV)	104	110	118	129	139	170
Case 2 (kV)	144.6	244.5	435.4	687.3	843.7	1198.3
Case 3(kV)	177.7	337.4	714.2	1337.8	1773.0	3057.0

Table 4.2- Voltage stress at transformer HT bushing

This variation can be illustrated as in the Fig. 4.2 BIL level of transformer is also presented in this figure.

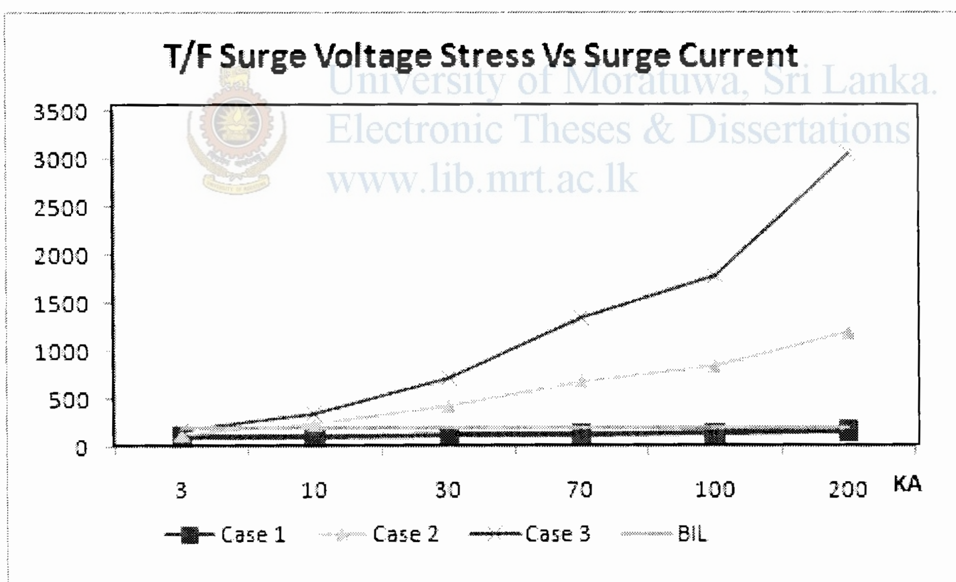

Fig. 4.2 – Variation of transformer surge voltage stress with surge current

These data reveals that transformer constructed as in case1 (Zero lead length) is well protected under designed BIL. But in case 2 (lead length =0.5m), voltage stress exceeds BIL level of transformer at about 10 kA of surge current. Therefore, it is recommended to construct substation with zero lead length to minimize damage by transient overvoltages.

Chapter 5

Sensitivity Study of Transient Overvoltages using PSCAD Models

The PSCAD software is especially dedicated to transient simulations of power systems. The user-friendly graphical user interface (GUI), the numerous control tools, its fast execution speed and interactivity make PSCAD a convenient tool for the analysis of behaviour of transient overvoltages in distribution network. It is used in planning, design, developing new concepts, testing ideas, understanding what happened when equipment failed, commissioning, preparation of specification and research. The user can enter the parameters of the conductors (resistivity, radius, and bundle information) and geometrical layout of conductors on the tower (distances between conductors, sag) [7].

5.1 Model for Lightning Surge (Wave Form)

Lightning, as a physical phenomenon, corresponds to an impulse current source that is a series discharge of a quantity of electricity over a short period of time. The actual wave form is quite variable and comprises a steep front to the maximum amplitude, followed by a long decreasing tail of several tens of microseconds. For the purpose of surge calculations, it is only the heavy current flow during the return stroke that is of importance. During this period it has been found that the wave form can be represented by a double exponential of the form [5]

$$I_{Test} = \mathbf{I}\,(\mathbf{e}^{-\alpha t} - \mathbf{e}^{-\beta t})$$

The values of I, α and β of the above equation may be determined for the impulse wave if the crest value and time to crest and time to half settle on the tail are known. The standard voltage wave form used in the high voltage testing has a 1.2/50 micro sec wave form to take into account the most severe conditions. Wave form of a simple lightning surge can be represent by [7]

I = 1.02*I1 * [EXP(-13000 * t) - EXP(-4.4E6 * t)]

5.2 Models to Study Transient Overvoltages in Tower Line and Pole Line

For simulation of atmospheric overvoltages it is necessary to create tower models, pole line models and their combination characterized by their electrical parameters. The tower and conductor geometry is required to calculate the line constants for transmission line models in PSCAD. From the Tlines pages in Master Library, configuration closet to the overhead distribution line can be selected. The distributed transmission line models operate on the principle of traveling waves. A voltage disturbance will travel along a conductor at its propagation velocity (near the speed of light) until it is reflected at the end of the line. There are three distributed transmission lines available in the Tlines pages of Master Library. These are in order of increasing precision as Bergeron model, Frequency Dependent (Mode) model and Frequency Dependent (Phase) model. Frequency dependant (Phase) model was selected in this research because it represents the full frequency dependence of all line parameters and it is useful for studies wherever the transient behaviour of the line is important. For each distribution line represented in the network diagram dimensions and data required [7].

The transmission line data required includes:

- Transmission line conductor diameter and resistance per unit length
- Total length of each transmission line
- Spacing between phase
- Shield wire diameter and resistance per unit length
- Height of each conductor and shield wire at the tower and sag to mid span
- Tower/ pole dimensions
- Ground conductivity

The simplest representation is a lossless distributed parameter transmission line, characterized by surge impedance and a travel time.

The surge impedance of a line can be calculated as follows.

$$Z_0 = \sqrt{\frac{l}{c}} = \sqrt{\frac{\mu_0}{\varepsilon_0}\left(\frac{\log_e d/r}{2}\right)^2}$$

Where **r** is the radius of conductor and **d** is the conductor spacing.

But

$$\frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$ is velocity of light.

Substituting the velocity of light as 3x10^8 m/s and simplifying gives

$Zo = 60 \log_e (d/r)\ \Omega$

The radius of Raccoon conductor r =0.00606m and conductor spacing d =1.1m

Therefore surge impedance of distribution line can be calculated as

$Zo = 60*\log_e (1.1/.00606)$

$= 312\ \Omega$

The line termination at each side of the above model needed to avoid reflections that could affect the simulated overvoltages around the point of impact is represented by a long enough section with its surge impedance. A lightning stroke is represented as an ideal current source whose parameters are determined by a model to represent lightning wave form as described in the chapter 5.1.

Models used to study transient over voltages due to lightning surges in tower line (Model 1), pole line (Model 2) are attached in Appendix B.1 and Appendix B.2.

5.3 Sensitivity Study to Analyze Surge and Line Parameters.

Sensitivity studies can be very useful to analyze the influence of line and stroke parameters, and to determine what range of values might be concerned. Although the number of parameters involved in lightning calculations is high, only some of them can be simulated from the line geometry. The tower, pole and conductor geometry is required to calculate the line constants for all distribution line models. Availability of earth wire and its position can be edited with these models. Size of the conductors and their electrical properties, details of line sags and details of ground properties can be edited as required. When transients are being studied, the whole network usually does not need to be modeled. To minimize reflection effects if an overhead distribution line is modeled for fast fronts with a shorter length, they can be terminated by resisters representing the surge impedance.

Transient Overvoltage Variation with Peak Current Magnitude of Surge Current

Lightning strike on a phase wire was simulated using model 1 and model 2 in Appendix B, surge voltage of the phase wire was measured for different peak value of lightning currents and shown in the Fig. 5.1. In this case striking distance was adjusted to 0.5 km.

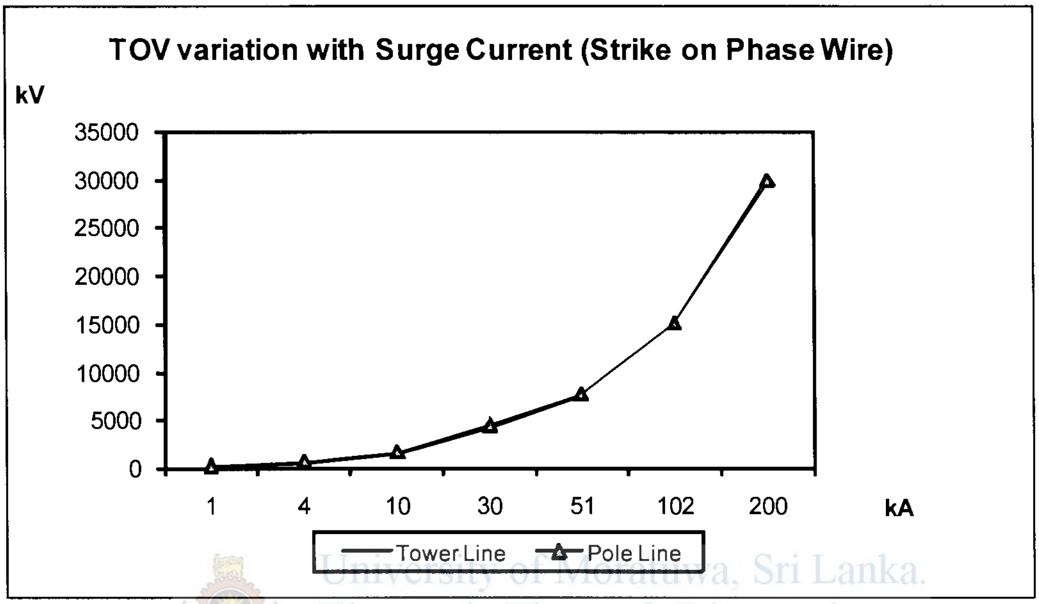

Fig. 5.1- TOV variation with magnitude of peak current (Strike on phase wire)

This figure shows that as magnitude of surge peak current increases, transient overvoltage exceeds up to mega volt range. Although there are differences in line parameters, same performances are shown in tower and pole lines. Since the designed value of BIL is 200 kV, if a direct strike happens on a phase wire, insulators may get damaged and cause earth faults. Due to the availability of shield wire, tower lines are well protected from direct lightning strokes, but pole lines are vulnerable for them.

Strike on earth wire was simulated with same models and measured the voltage in phase wire. Results are shown in the Fig. 5.2. This figure also shows that, increase of surge peak current result in increase of transient overvoltage in phase wire, but these values are limited at designed BIL level. Hence it is revealed that the introduction of shield wire reduces the risk of flashovers because the grounded conductor reduces the voltage stress across the insulation through capacitive coupling. Adding the grounded wire below the phase conductors reduces the performance than the over overbuilt shield wire. A grounded overhead shield wire will reduce the voltage across the insulation by a factor which depends on grounding and proximity of the grounded conductor to the phase conductor. Since the shield wire is grounded, it will suppress the voltages on the phase conductors through capacitive coupling. The closer the phase wire, the better the coupling, and smaller the induced voltages will be (although this may reduce the CFO). Note that adding a grounded wire below the phase conductors will have approximately the same effect as an overhead shield wire. This factor is typically between 06 and 0.9. The grounded circuit has fewer flashovers for given CFO because the grounded conductor reduces the voltage across the insulation [6].

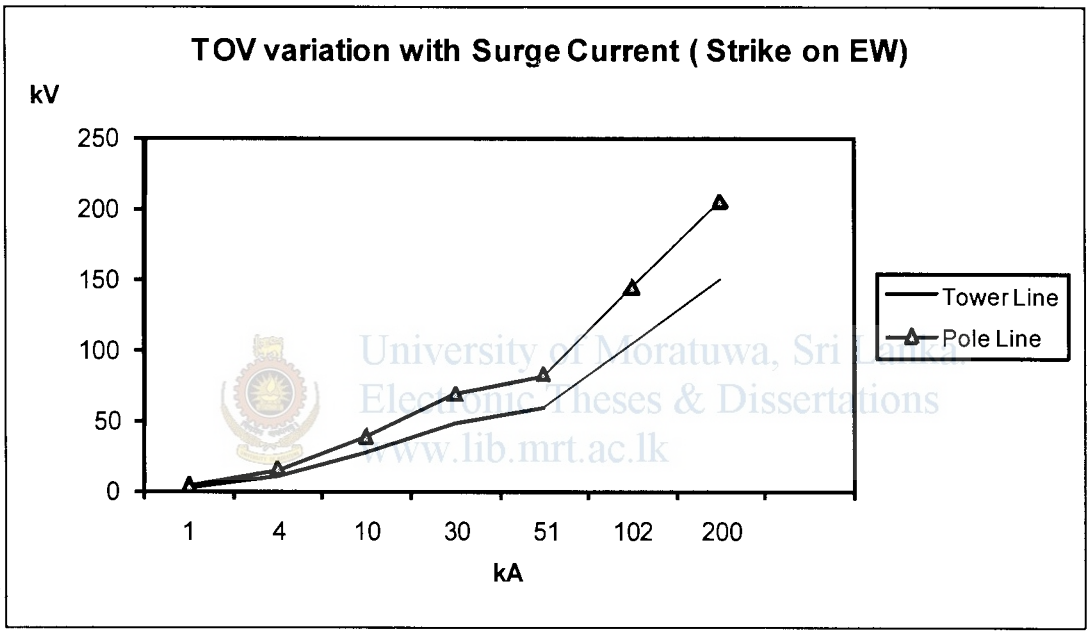

Fig. 5.2- TOV variation with magnitude of peak current (Strike on earth wire)

Transient Overvoltage Variation with Earth Rod Resistance and Soil Resistivity

For properly designed lines, having well located shield wires, most lightning strikes to the line will terminate on the shield wire. The current surge will travel along the shield wire until it reaches a structure where it will be conducted down into the ground. The grounding of structures is never perfect and causes a voltage rise of the structure above ground voltage. At the same time, voltage is induced on the phase conductors through capacitive coupling. The model 2 (pole line) was checked for strike on earth wire by varying earth wire grounding resistance (impulse resistance) and obtained peak values of transient voltage waveforms on phase wires. Data are shown in the Fig. 5.3.

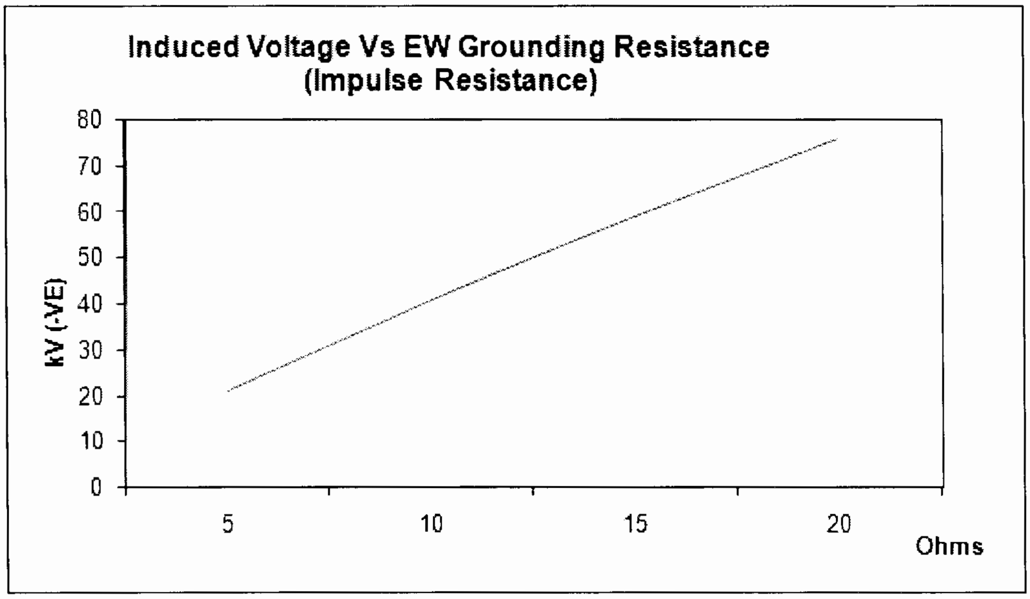

Fig. 5.3- TOV variation with EW grounding resistance

This graph clearly shows that voltage stress increases with high resistance values. Reduction of voltage stress by grounded wire depends on value of earth rod resistance and soil resistivity in the location. Measured values of soil resistivity (Appendix B.4) shows that high values such as 792 Ω-m is available in high altitude areas. Variation of voltage stress with increase of soil resistivity is shown in the Fig 5.4.

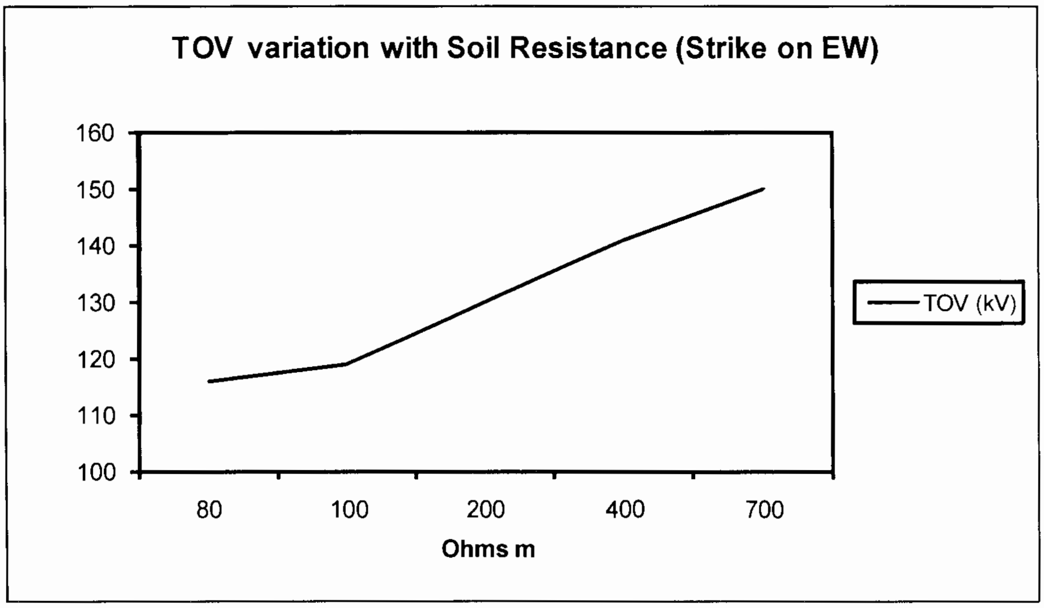

Fig. 5.4- TOV variation with increase soil resistivity

Transient Overvoltage Variation with Striking Distance.

In this study four different striking point distances were studied with surge current of 30 kA. Adjusting the length of feeder line in each model, we can simulate lightning surge at different striking distances. For each distance, corresponding overvoltage was measured and peak values of obtained waveforms are plotted in the Fig. 5.5. These results show that transient overvoltage is higher as the measuring point is closer to the striking point.

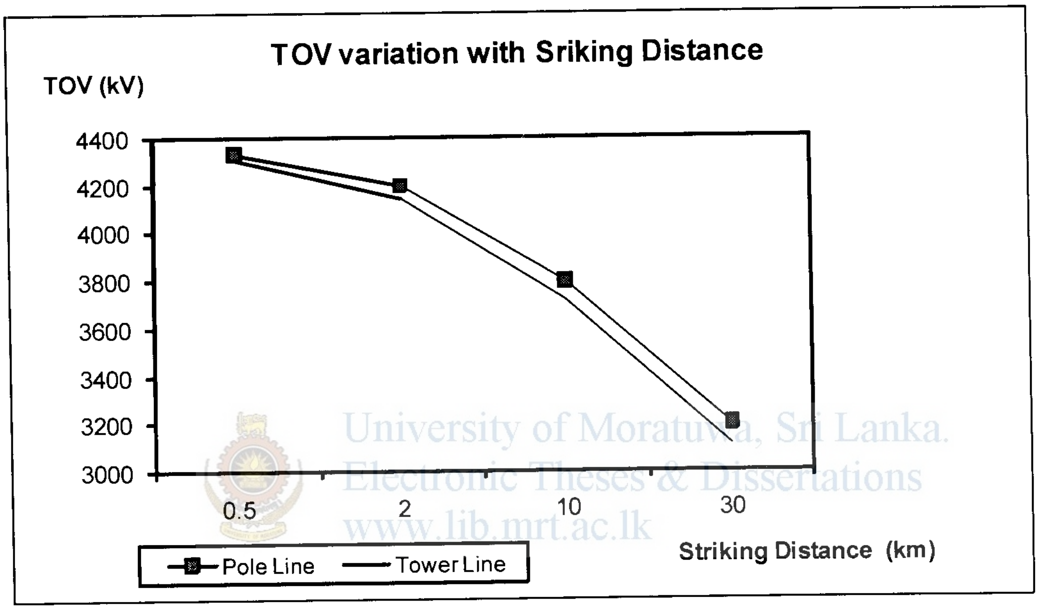

Fig. 5.5- TOV variation with striking distance

5.4 Analysis of Performance of Surge Arresters

Metal oxide surge arresters (MOVS) are used in distribution networks to reduce the system voltage stresses due to transient overvoltages.

For IEEE arrestor model (Fig. 5.6), there is two sections of non linear resistance designated AO and AI each comprised of the surge arrester model used for switching surge transients [7].

If d is the height of the arrester (0.385 m)

Then $L1 = 15d = 15*.385 = 5.777\ \mu H$

$R1 = 65d = 65*0.385 = 25\ \Omega$

$L0 = 0.2d = 0.2*0.385 = 0.077\ \mu H$

$C = 100/d = 100/0.385 = 259\ pF$

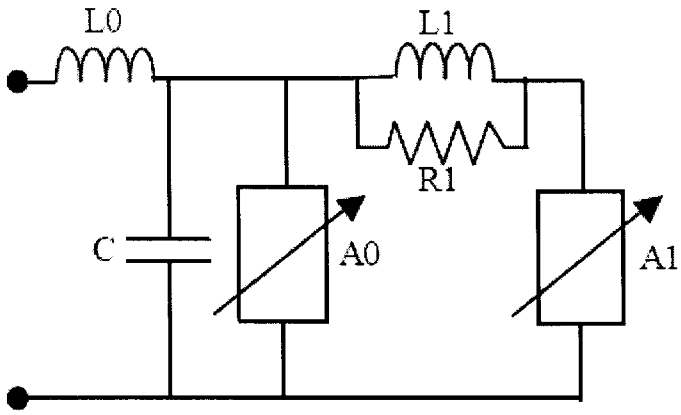

Figure 5.6- IEEE surge arrester model

CEB specification for surge arrester is as follows

Rated Voltage - 36 kV

Maximum continuous operating voltage (MCOV) – 29 kV

MCOV is defined as the maximum power frequency voltage that an arrester is designed to withstand continuously. Our model is based on a surge arrester having 10 kA discharge voltage of 89 KV at 1.6 per unit (crest value). Then the arrester voltage rating was considered as 89/1.6, i.e. 55kV.

Lightning arresters are used in 33 kV network to protect distribution transformers from lightning effect. The Model 3 in Appendix B.3 is used to simulate a distribution transformer protected by lightning arresters and DDLO fuses. In fast front studies transformers are represented by capacitance coupling. Parameters like arrester current, voltage and energy absorption were studied by injecting a lightning current to the distribution line at a distance of 0.5 km.

The magnitude of peak surge current increase and resultant arrester performance values are shown in the Fig. 5.7. This figure shows that, with the increase of surge current, the peak voltage, arrester current and energy absorption increases simultaneously. The amount of energy that an arrester can absorb reliably in a lightning flash without suffering irreversible damage or overheating is specified by the manufacturer. This value is generally specified in kJ per kV of MCOV. Approximate value is 2.2 kJ/kV. Hence energy absorption in 10 kA arrester is 63.8 kJ (2.2 x 29). High surge currents (over 10 kA) cause very high energy dissipation across the arrester causing arrester failure.

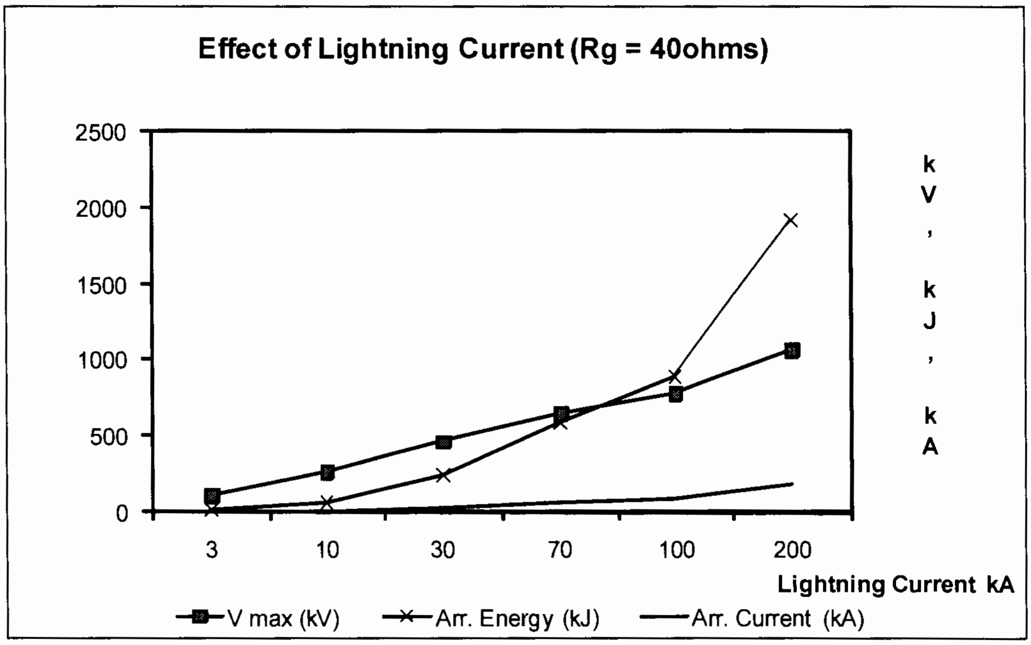

Fig. 5.7-- Arrester performance with the magnitude of surge current

All of the surge arresters are designed for the effective grounding. But it is found that earth resistance in substations in various places varies from about 12 Ω to high values such as 90Ω (Appendix B.4). Therefore, using this model surge current (10 kA) was simulated to check the arrester performance with different earth rod resistances and results are shown in the Fig. 5.8.

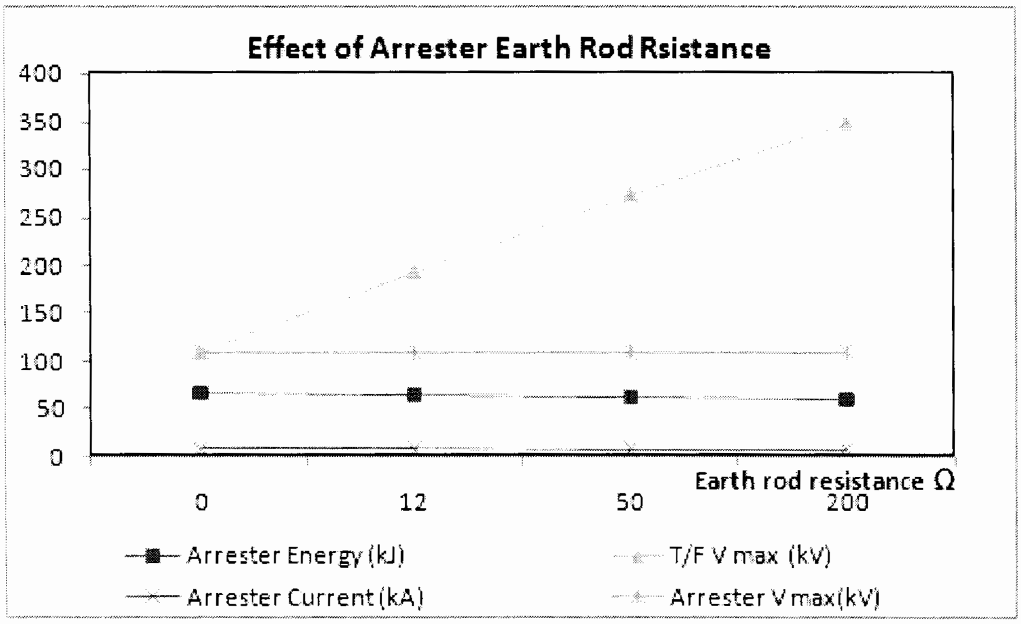

Fig. 5.8- Arrester performance with earth rod resistance

Voltage stress at the transformer HT side was measured with reference to the earth potential. This simulation shows that with the increase of earth rod resistance, current through the arrester decrease and simultaneously reduces the energy absorption. But voltage across the arrester keeps same level but increases voltage stress at transformer (reference to the earth potential). These data reveals that, for earth resistance of 12 ohms, voltage stress obtained at transformer is 194 kV. Therefore it is recommended to maintain low earth rod resistance (below 12 Ω) to achieve expected protection for distribution transformer.

5.5 Analysis of Nuisance Fuse Blows

The amount of energy required to melt high voltage expulsion fuses is a constant for all current of short duration, such as lightning surges.

Whether or not a fuse will be blown by a lightning surge can be determined by measuring the ampere-square second (I^2t) of the surge current and comparing it with the I^2t level required to melt the fuse [9].

With the use of product block (IxI) and integral block (t) in the model 3, this I^2t value can be calculated for different surge currents.

For a surge current of 6 kA, obtained I^2t value is 1136 A^2s, But details given by the Cooper Power Systems [9] for 6K fuse has its I^2t value of 500 A^2s. And 6T fuse has 1500 A^2s. Therefore 6K fuse may blow with that surge current and 6 T fuse can withstand it.

5.6 Surge Durability in Surge Arrester and DDLO Fuse Connection

In the CEB distribution sub stations, DDLO Fuse link is fixed at the source side and arrester is fixed at the transformer side (load side). If the arrester is on source side, surge arrester failure could cause loss of a large part of the system. Traditionally, the concern for fuses being damaged by lightning has been addressed by connecting the arrester to the source side of the cutout. This way, the bulk of the surge current is bypassed before it reaches the cutout. These two arrangements in connecting arresters and DDLO fuses in distribution substation can be simulated by Model 3. Circuit in Model 3 represents the connection of arrester at load side. By shifting the position of breaker in between arrester and transformer the second arrangement can be simulated. Model of the DDLO fuse was developed by using a breaker and its time current characteristic.

These simulations show that, when the arrester is connected at source side, no fuse blowing happens. But when the connection of DDLO is at source side, fuse failures can be observed according to the rating and severity of the surge current.

Table 5.1 gives data obtained from the simulation.

Surge current kA	**Fuse 3A**	**Fuse 5A**	**Fuse 8A**
10	Fused	No	No
50	Fused	Fused	Fused
100	Fused	Fused	Fused

Table 5.1- Data obtained from simulation of fuse blowing

Simulations were done for the following combinations and observed results are:

- Connection with DDLO fuse only (Without surge arrester)

If fuse is not blown, TOV at source side is 4659 kV

If fuse is blown, TOV at source side is 10991 kV

- Connection with DDLO fuse at source side and arrester at load side

If fuse is not blown, TOV at source side is 263kV

If fuse is blown, TOV at source side is 10390kV

- Connection with arrester at source side and DDLO fuse at load side

If fuse is not blown, TOV at source side is 263kV

If fuse is blown, TOV at source side is 263kV

Fig. 5.9 shows the wave forms obtained from simulations for transient overvoltages at source side and load side. These figures show that as the fuse is blown, surge stress increases at the source side. The results of above simulations prove that the best method of connection is to have the surge arrester at striking side and DDLO fuse fixed at load side.

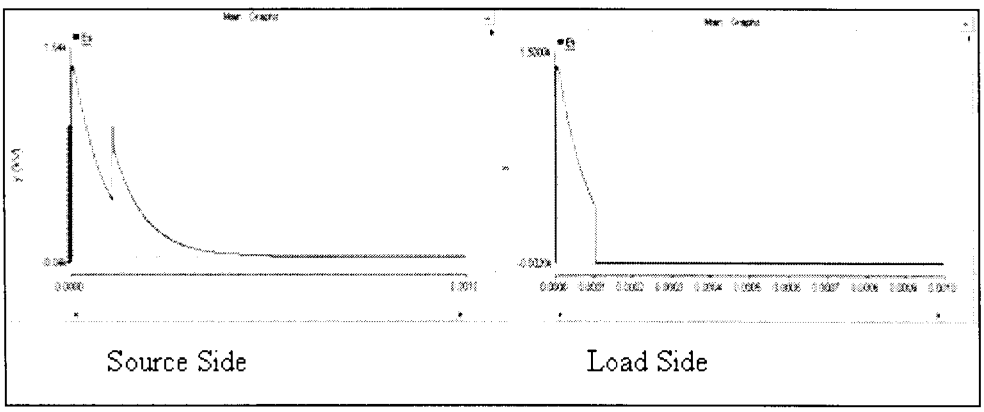

Fig. 5.9- Wave forms obtained from simulation of fuse blowing

Chapter 6

Proposals for Improvements of Surge Performances

6.1 Zero Lead Length Application in Distribution Substation

The purpose of an arrester is to limit the voltage stress on the insulation electrically in parallel with it, during surge event. The voltage stress on the insulation in parallel with the arrester is the sum of the arrester residual voltage and the inductive voltage of leads. It is proven in the Chapter 4.2 that longer the leads, the higher the voltage created by the leads during surge.

Substations described in Case 2 and Case 3 in Chapter 4.2 can be changed in to zero lead length configuration by

- Moving the line lead from top of the transformer to the top of the arrester (Case 2)
- And adding earth wire between the arrester base and the transformer tank. (Case 3)

Construction of distribution substations in present specification, i.e. DDLO fuse at source side and surge arrester at transformer side has following problems.

- Conducting arrestors blow fuses (Nuisance fuse blows are high)
- High outage time
- And transport cost

But in the configuration of arrester at source side, arrester failure may cause power failure for large part of the system. Also there is no way of knowing when arrester is spent. If arrester and DDLO fuse link can be connected in a parallel combination to the transformer tank then the advantages described above can be achieved.

The Transformer Combi Unit (Fig. 6.1) placed at pole mounted transformers ensures that the fuse is removed from the lightning path eliminating nuisance blows [11]. The surge arrester is critical to the operation of the Transformer Combi Unit. The unit allows the arrester to be dealt with the lightning transient by providing and maintaining a healthy path to earth. Once the surge arrester is spent, it alerts the operator by dropping out. It has a facility on its pole clamp, for the spare arrester which then can be replaced on the spot. The customer experiences a much better quality of supply, due to the surge arrester enhanced protection capabilities protecting both the transformer and fuses.

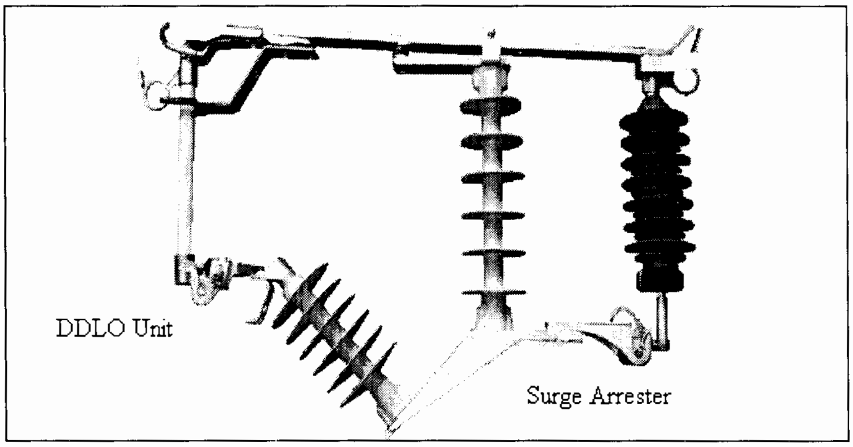

Fig. 6.1- Transformer Combi Unit of Live Line Technology

6.2 Use of Surge Durable Fuse Links

In selecting fuses for transformer protection, a key element that is usually overlooked is that of lightning. Use of fuses with high surge withstand capabilities is the one answer for nuisance fuse blowing. T type fuse links provide slower time characteristic than the K type fuse. Use of slow fuse with high rating exposes the transformer to failures due to overloads. The multiple element design of D link combines the overload protection of small amp links and the high surge (I^2t) capability of high amp links. The minimum melt Time Current Characteristic (TCC) curves in Fig. 6.2 illustrate the duel element characteristic of the D link fuse and its high surge (I^2t) capability [9].

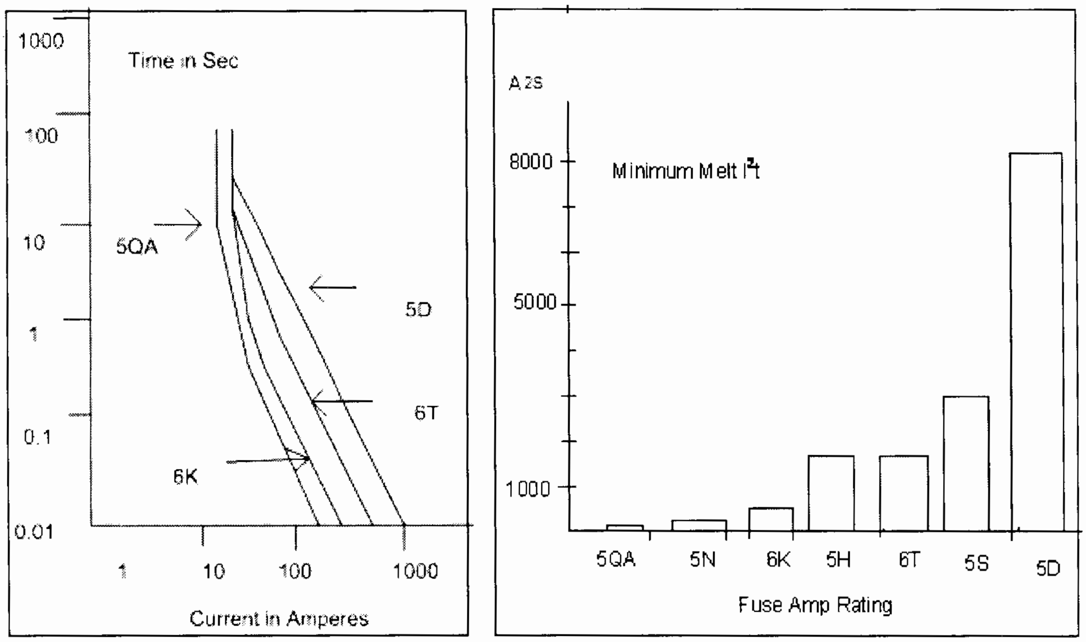

Fig. 6.2 - Time Current Characteristic (TCC) curves and I^2t values of fuses

6.3 Introduction of Lightning Proof Fuses

The Lightning Proof Fuse (LPF) is a convenient and cost effective method of over current protection, with the advantage of eliminating nuisance fuse blows. Operation of the LPF is described in the Fig. 6.3. The power frequency flows through the inductance coil and the standard fuse link. The coil allows the system frequency current to operate through it, but blocks high frequency transients, not allowing these high transients to flow through the fuse. The high frequency transient is by-passed via an arching horn.

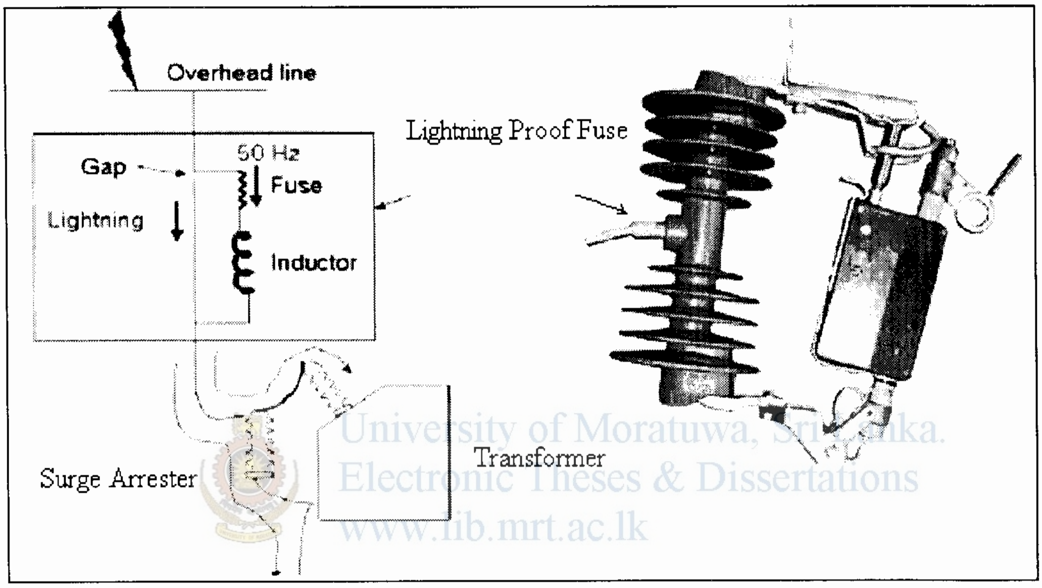

Fig. 6.3 – Lightning Proof Fuse

6.4 Use of Surge Arrester in Connection between Pole Line and Tower Line

As described in Chapter 5.7 the best method of connecting arrester which minimizes stresses is the one having surge arrester at striking side and DDLO fuse fixed at load side. Since there are more lightning prone pole lines in hilly areas, it is recommended to fix surge arrester at strategic points in poor performing spur lines. The arrester should be fixed at pole line side next to the DDLO cutouts. If a drop down type arrester (Described in Chapter 6.1) is used in this application then total feeder failures due to fail of arrester can be eliminated.

6.5 Other Improvements

Other proposals for improvements are:

- Reduction of span length of grounding points of overhead earth wire

  The current flowing into the ground wire reduces the induced voltage due to electromagnetic coupling between an overhead ground wire and phase conductor. Earth wire of pole lines are grounded at tension points only. Sometimes these span lengths exceed over 200 m. Shortening the grounding interval for overhead earth wire reduces the voltage stress linearly, but it is not possible to limit failures drastically [12].

- Avoid connecting stay wire to the cross arm assembly of pole structure

  Since the stay insulators are having less BIL level (30 kV), strikes may flashover through stay wire to the ground.

- Avoid of fixing pin insulator to towers

  Sometimes pin insulators are used in tapping points. Since tower lines consist of suspension insulator strings, insulation levels is over 320 kV. But with the introduction of pin insulators, insulation level may reduces up to 180 kV.

- Maintain specified clearances between phases and earth wires

  Air insulation level is 600 kV/m. Due to the variation of sags and other reasons, air gap between phase and earth wires shortens and reduces the insulation level.

- Properly fixing of DDLO cutouts and other equipment

  Most of these equipments possess less BIL. Therefore proper installation is required to maintain clearance between grounded parts.

- Cleaning of insulators, bushings etc.

  Deposits of pollutants may increase with aging. Therefore proper maintenance programmes must be adopted to clean and wash these insulators.

- Maintain the way leave clearances

  Proper way leaves clearance program may increase the line insulation level significantly (Increase of air gap).

Chapter 7

Conclusions

Reasons for over half of the feeder failures and MV breakdowns are caused by weather related incidents. During the year 2008, transformer failure rate was 2% of its total population and much higher than the acceptable level (0.5%). The main reasons were damages due to lightning. Since no specific reason is reported for HT fuse failures in substations, a large number of HT fuse failures can be considered as nuisance fuse blowing. About 37 % of lightning related failures can be observed from the total MV failures of the Uva province. Therefore it is clear that failures due to transient over voltages play major impact to the reliability of MV network and hence study of transient over voltages and mitigation measures are very important to improve the quality of the supply.

Most of the 33kV feeder lines in the Uva province are very lengthy (over 250km) and cover different geographical areas. These lines consist of both tower and pole line combination and most of the spur lines are having short distances, but over 10 km length of spur lines are also available. Due to the variation of line height, insulation levels and availability of shield wire, performance against transient overvoltages differ from tower line to pole line. Some overhead lines in the system are installed on high ridges which are predominant in this region, exposing and making them vulnerable to lightning. Study of shielding effect reveals that in some of the spur lines, nearby trees are not high enough to protect the lines from direct strokes. Therefore, the shielding factor can be considered as less than 0.5 for this type of lines.

Therefore, direct connection of spur lines (Pole Lines) to tower line affect the performance of the main feeder. It is recommended to fix surge arrester at strategic points in poor performing pole lines to improve line performance. Line performance in pole lines which are not shielded by nearby trees can be improved by adding overbuilt earth wire and reducing the span length of grounding points.

Estimated flashover rates (Direct and Induced) of feeder lines reveal that feeder lines which are having more line length, running over high ground flash density areas and having more spur lines are subjected to more flashovers. Feeder 6 (Passara feeder) shows the most poor lightning performance (291 flsahes/year).

Since the cross arm assembly is earthed in pole lines, the lowest CFO level is found for flashover path from phase wires to earth wire through pin insulator (180 kV). The BIL value of the stay insulator is 30 kV, therefore the next flashover path having lowest CFO value is flashover through pin insulator to stay wire. Test values show that most of the surface damaged insulators satisfy the designed insulation levels, but insulators covered with moss are having less insulation level. Thickness and severity of deposited pollutant may increase with the aging of the feeder line and found that age of most of the feeder lines are over 10 years.

Lightning surges continue to be the major cause of premature transformer failures. Fast rise time surges that generate excessive voltage through the primary arrester and connecting leads may affect the surge performance of distribution transformers. Arrester lead length becomes critical during a lightning discharge because it generates high voltage stress which may fail distribution transformer. Hence, it is recommended to construct substation with zero lead length to minimize damage by transient overvoltages. Therefore it is recommended to revise the specifications and drawings in CEB construction manuals. If arrester and DDLO fuse link can be connected in a parallel combination to the transformer tank then the advantages described above can be achieved. Also, laboratory test should be done to identify the cause for failed transformers and then to revise specifications for BIL values and their protections.

Sensitivity studies using PSCAD models reveal that in case of strikes to phase wire, transient overvoltage exceeds up to mega volt range. But, introduction of shield wire reduces the risk of flashovers from direct and induced stokes. Transient overvoltage is higher in places close to the striking point. Also, voltage stress increases with high earth rod resistance values. This is same for high soil resistivity values, especially in high altitude areas.

Simulation of surge arrester performance shows that with the increase of surge current, the peak voltage, arrester current and energy absorption increases simultaneously. High surge currents (over 10 kA) cause very high energy dissipation across the arrester causing arrester failure. Therefore it is recommended to maintain low earth rod resistance (below 12 Ω) to achieve expected protection for distribution transformer. Testing and early identification of arrester performance is a key step to be taken to minimize transformer failures.

Connecting lightning arrester at source side reduces nuisance fuse blows. Whether or not a fuse will be blown by a lightning surge can be determined by measuring the ampere-square second (I^2t) of the surge current and comparing it with the I^2t level required to melt the fuse. Use of multiple element design fuse links (D link) with high surge (I^2t) capability is a solution for nuisance fuse blows. Use of lightning proof fuse is another application to reduce it. High rate of HT fuse blowing can be minimized by having a proper coordination between HT and LT fuses.

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Appendix A

Definitions

Back flashover (lightning): A flashover of insulation resulting from a lightning stroke to a part of a network or electric installation that is normally at ground potential.

Basic impulse insulation level (BIL): A reference impulse insulation strength expressed in terms of the crest value of withstands voltage of a standard full impulse voltage wave.

Critical impulse voltage (CFO): The crest value of the impulse wave that, under specified conditions, causes flashover through the surrounding medium on 50% of the application.

Direct stroke: A lightning stroke direct to any part of a network.

Ground electrode: A conductor or group of conductors in intimate contact with the ground for the purpose of providing a connection with the ground.

Ground flash density (GFD): The average number of lightning strokes per unit area per unit time at a particular location.

Indirect stroke: A lightning stroke that has not directly strikes any part of a network but induces an overvoltage in it.

Induced voltage: The voltage induced on a network or electric installation by an indirect stroke.

Line lightning performance: The performance of a line expressed as the annual number of lightning flashovers on a circuit mile.

Overhead ground wire (OHGW): Grounded wire placed above phase conductors for the purpose of intercepting direct strokes.

Shielding angle: The angle between the vertical line through the overhead ground wire and a line connecting the overhead ground wire with the shielded conductor.

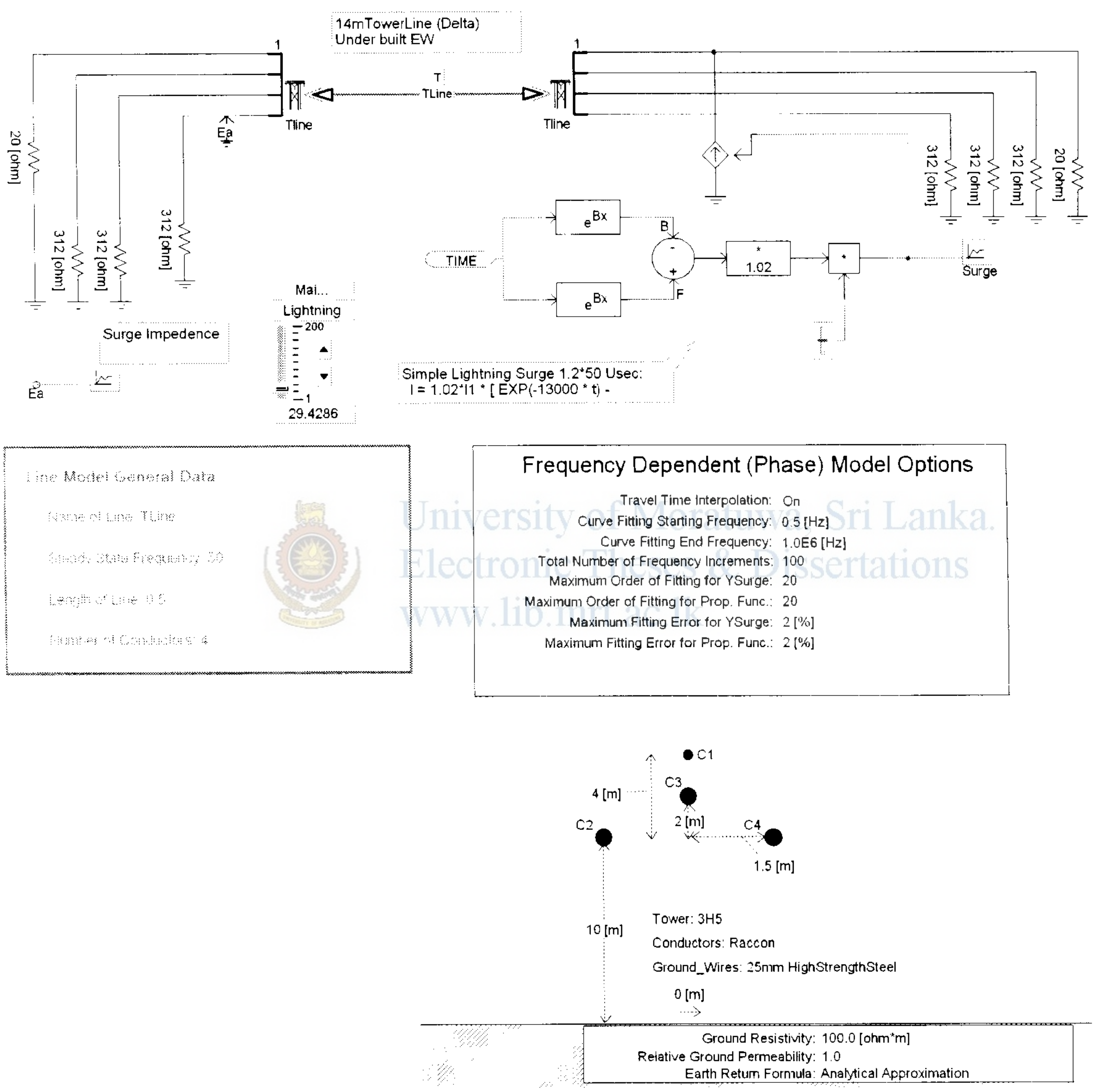
Shield wire: grounded wire placed near the phase conductors for the purpose of protecting phase conductors from direct lightning stroke and reducing induced voltages from external electromagnetic fields.

Surge arrester : A protective device for limiting surge voltages on equipments by diverting surge current and returning the device to it's original status.

Appendix B

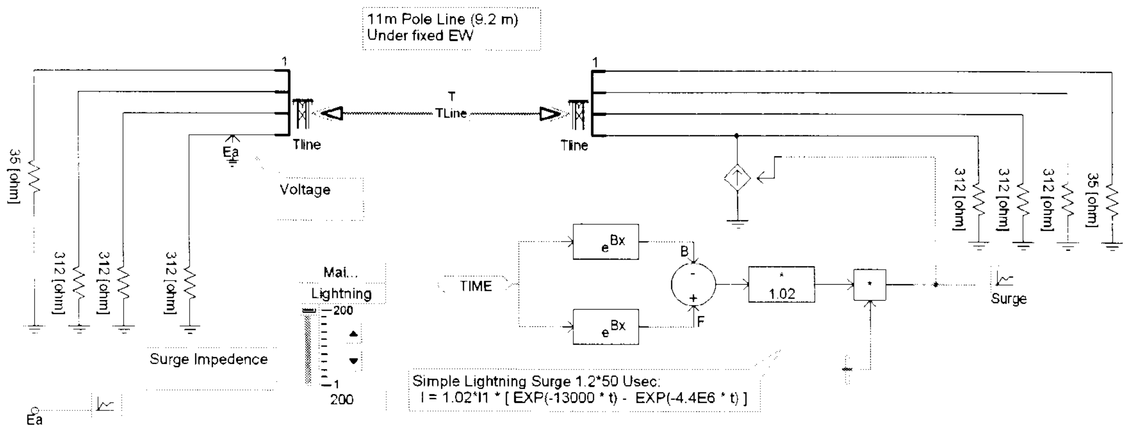
Appendix B.1

Model 1-PSCAD model for Tower Line



Appendix B.2

Model 2 -PSCAD model for pole line



Line Model General Data

Name of Line: TLine

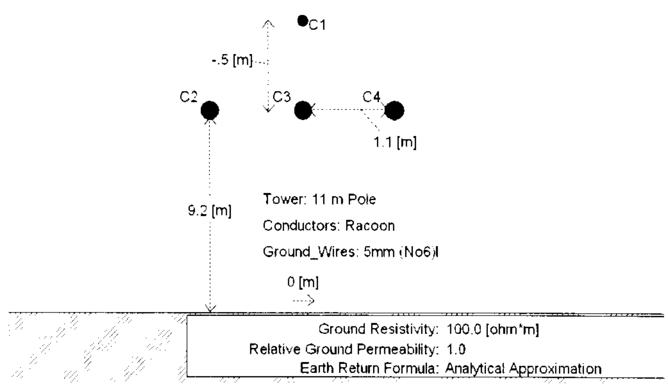
Steady State Frequency: 60

Length of Line: 0.5

Number of Conductors: 4

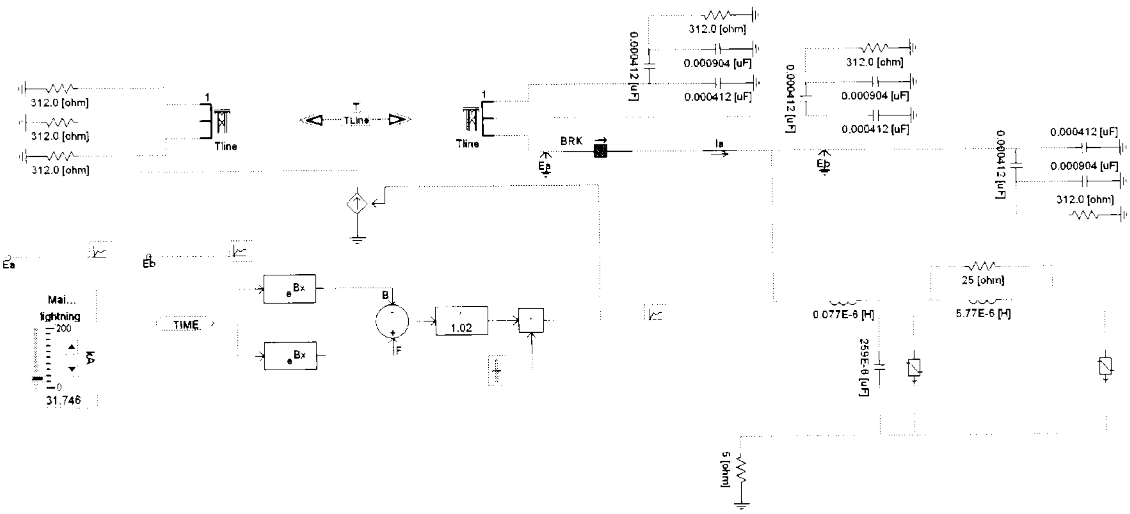
Frequency Dependent (Phase) Model Options

Travel Time Interpolation:	On
Curve Fitting Starting Frequency:	0.5 [Hz]
Curve Fitting End Frequency:	1.0E6 [Hz]
Total Number of Frequency Increments:	100
Maximum Order of Fitting for YSurge:	20
Maximum Order of Fitting for Prop. Func.:	20
Maximum Fitting Error for YSurge:	2 [%]
Maximum Fitting Error for Prop. Func.:	2 [%]

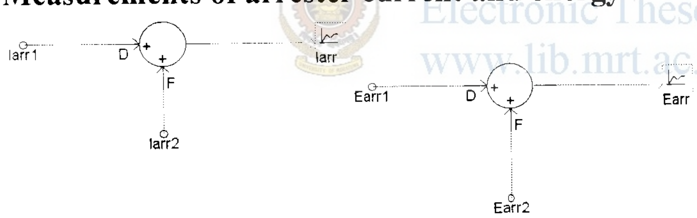


Appendix B.3

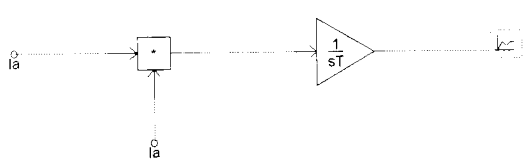
Model 3-PSCAD model for distribution substation



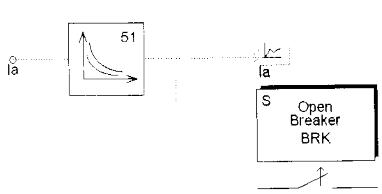
Measurements of arrester current and energy



Measurements of I^2t value



Represent of DDLO fuse by breaker with time current characteristic



Appendix B.4

Measured Data

Soil Resistivity

Location	Soil Resistivity (Ω-m)
Springvalley- Near DB-10	118
Springvalley- Near DB-08	143
Haliella	607
ITN	792
Wellawaya	17
Buttala	118

Earth Resistance of Substations

Name of the Substation	Resistance-Ω
Bandarawela Supermarket	41
Bandarawela Ford Sub	73
Bandarawela Sisira Garage	14.4
Bandarawela Prise Rd Sub	93.5
Dikarawa	18
Bandarawela Hospital Sub	82.3
Bindunuwewa	23.7
ITN Sub	70
Vidya Peeta	23
Farm	12.1

Tower Foot Resistance
Namunukula Feeder

Tower Name	Resistance - Ω
DB-10	68.8
DB-9	17.2
Db-8	195.9
Poonagala	53.5
ITN	44.4
Koslanda	48.2
Wellawaya	3

Appendix B.5

Test Values of Flashover Voltages

Insulator	Surface flashover %	Dry Flashover Voltage	Wet Flashover Voltage	Dry Impulse Voltage	Wet Impulse Voltage
A 3 Disk Set	A1- 4.6%, A2- 1.3%, A3- 9.05%	>85kV	>85kV	>300kV	>300kV
B 3 Disk Set	B1-1.3%, B2-1.0%, B3-4.9%	>85 kV	>85 kV	>300kV	>300kV
C 3 Disk Set	C1- 4.2%, C2- 0.5%, C3-0.4%	>85 kV	70 kV Flashover	>300kV	284 kV Flashover
D 3 Disk Set	D1- 4.8%, D2-0%, D3-0.9%	>85 kV	>85 kV	>300kV	>300kV
E 3 Disk Set	0%, But totally covered with Moss	>85 kV	77 kV Flashover	290 kV	282 kV Flashover
B1 Single disk	1.3%	77 kV	43 kV Flashover	258 kV Flashover	
C3 Single Disk	0.4%	76 kV	43 kV Flashover	-	
F1 Single disk - new	0%	82 kV	43 kV Flashover	>300kV	
F2 Single disk - new	0%	83 kV	43 kV Flashover	>300kV	
F3 Single disk - new	0%	81 kV	43 kV Flashover	>300kV	