Chapter - 1
Introduction

1.1 Historical overview of lightning

In June 1752, an American scientist called Benjamin Franklin (1706–1790) discovered the lightning as a natural phenomenon associated with discharging static electricity by his famous kite experiment accompanied by his son as an assistant (Shown in Figure 1.1).

Figure 1.1 – Benjamin Franklin's famous kite experiment in 1752

As he discovered, the lightning is a natural phenomenon involving an atmospheric discharge of electricity accompanied by thunder, which typically occurs during thunder storms, and sometimes during volcanic eruptions or dust storms. These lightning strike leaders or in other words a heavy bunch of electric charges can reach travelling speeds about 10,000ms^{-1} and can form extremely high temperatures like 30,000^{0}C forming some frightening as well as fascinating events. It has been found in many researchers that there are around 16million lightning storms likely to be formed in the world every year.

The history of lightning is likely to be present even back in billion years ago where the life was not even evolved on our planet. Further it had been possible that the lightning involved in forming some organic molecules necessary for the formation of every life form [1].Harland and Hacker (1966) reported on a fossil glassy tube, referred to as a fulgurite, created by lightning 250million years ago [1].

Even though the Benjamin Franklin had showed that the lightning is a discharge of static electricity; the development of theoretical understanding was rises as the field of power engineering came in to practice, where the power transmission and distribution lines were severely affected by lightning. As a result there were lot of experiments on lightning and in 1900, Nikola Tesla generated artificial lightning by using a large Tesla coil, enabling the generation of enormously high voltages sufficient to create lightning.

1.2 The lightning phenomena

The present scientific explanation on how the lightning is formed is basically developed from the researches carried out by B.F.J. Schonland, D,J.Malan, and their co-workers in South Africa during the 1930s by facilitating a special camera called Streak Camera. It was shown conclusively by the South African researches that lightning strokes lowering negative charge to ground are composed of a downward leader and an upward return stroke and that the first stroke-leader is stepped. B.F.J. Schonland (1956) summarized the main results of the South African studies and much of the presently used lightning terminology was introduced by those studies [1].

1.2.1 Charge separation of thunder clouds

The very first process of generating lightning is considered as the charge separation in a thunder cloud. There are two hypotheses describing the process of charge separation in a thunder cloud called "Polarization mechanism" and "Electrostatic induction".

The Polarization mechanism has two sub components as mentioned below.

a) Falling droplets of ice and rain become electrically polarized as they fall through the atmosphere's natural electric field

b) Colliding ice particles become charged by electrostatic induction.

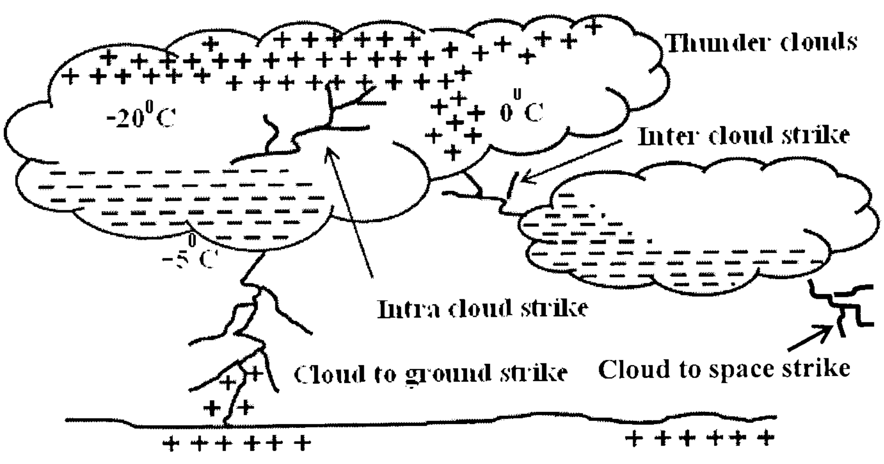

Figure 1.2 – Charge distribution of thunder clouds and types of lightning

Ice and super-cooled water are the keys to the process. Turbulent winds move violently these super-cooled water droplets, causing them to collide. When the super-cooled water droplets hit ice crystals, some negative ions transfer from one particle to another. The smaller, lighter particles lose negative ions and become positive; the larger, more massive particles gain negative ions and become negatively charged.

According to the electrostatic induction hypothesis charge separation appears to require strong updrafts which carry water droplets upward, super-cooling them to between -10 and -20^{0}C. These collide with ice crystals to form a soft ice-water mixture called Graupel. The collisions result in a slight positive charge being transferred to ice crystals and a slight negative charge to the Graupel. Updrafts drive lighter ice crystals upwards, causing the cloud top to accumulate increasing positive charge. The heavier negatively charged Graupel falls towards the middle and lower portions of the cloud, building up an increasing negative charge. Charge separation and accumulation continue until the electrical potential becomes sufficient to initiate lightning discharges, which occurs when the gathering of positive and negative charges forms a sufficiently strong electric field.

Therefore due to charge separation process, in most of the thunder clouds there is a Negative Charge Centre at the bottom of the cloud where the temperature is about -5^{0}C, whereas Positive Charge Centre appears at the top of the cloud at temperature about -20^{0}C. In addition to these there are localized positively charged region formed near the base of the cloud where the temperature is about 0^{0}C.

1.2.2 Electric fields and energy in thunder clouds

In a typical thunder cloud, the static charge of about 20C are separated by distances of about 3km whereas a field of about 1000V/m is existing near the center of the cloud giving a total potential difference between the charge centres to be between 100 to 1000MV. Therefore this type of charged cloud is capable of dissipating energy of the order of 1000 to 10,000MJ by a lightning stroke where much of the energy is spent in heating up a narrow air column surrounding the discharge to a temperature is about 15,000^{0}C within few microseconds [3].

Basically the static charge content of a bipolar charged cloud is in the rage of 10 to 30C whereas the charge centres are separated by a distances in the rage of 2 to 5km.The average current dissipated by lightning is of the order of kilo-amperes. During an average lightning storm, a total of the order of kilo-coulombs of charge would be generated, between the 0^{0}C and the -40^{0}C levels, in a volume of about 50km^3[3].

1.2.3 Leader formation and breakdown mechanism

As a thundercloud moves over the Earth's surface, an equal but opposite charge is induced in the Earth below, and the induced ground charge follows the movement of the cloud. An initial bipolar discharge, or path of ionized air, starts from a negatively charged mixed water and ice region in the thundercloud. The discharge ionized channels are called leaders. The negative charged leaders, called a "stepped leader", proceed generally downward in a number of quick jumps, each up to 50 meters long (See Figure 1.3). Along the way, the stepped leader may branch into a number of paths as it continues to descend. The progression of stepped leaders takes a comparatively long time (hundreds of milliseconds) to approach the ground. This initial phase involves a relatively small electric current (tens or hundreds of amperes), and the leader is almost invisible compared to the subsequent lightning channel.

When a stepped leader approaches the ground, the presence of opposite charges on the ground enhances the electric field. The electric field is highest on trees and tall buildings. If the electric field is strong enough, a conductive discharge (called a positive streamer) can develop from these points. As the field increases, the positive streamer may evolve into a hotter, higher current leader which eventually connects to the descending stepped leader from the cloud. It is also possible for many streamers to develop from many different objects simultaneously, with only one connecting with the leader and forming the main discharge path. When the two leaders meet, the electric current greatly increases. The region of high current propagates back up the

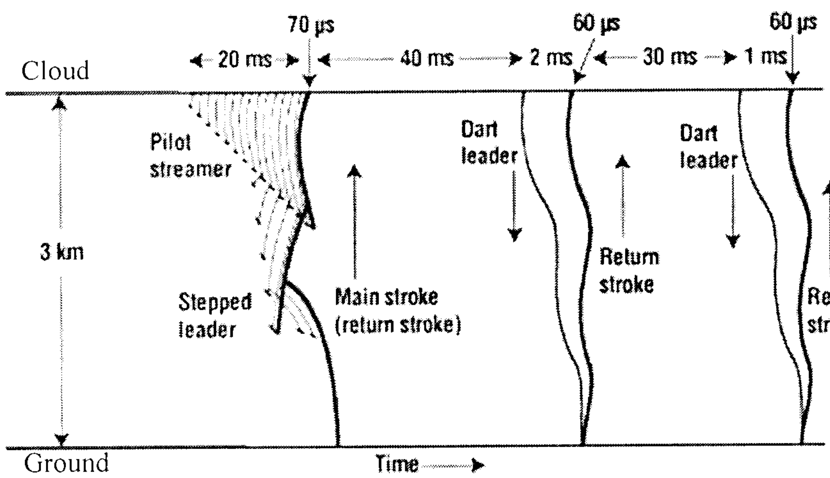

Figure 1.3 – Progression of the Downward Leader and formation of the Return Stroke

positive stepped leader into the cloud with a "return stroke" that is the most luminous part of the lightning discharge.

When the electric field becomes strong enough, an electrical discharge (the bolt of lightning) occurs within clouds or between clouds and the ground. During the strike, successive portions of air become a conductive discharge channel as the electrons and positive ions of air molecules are pulled away from each other and forced to flow in opposite directions. The electrical discharge rapidly superheats the discharge channel, causing the air to expand rapidly and produce a shock wave heard as thunder. The rolling and gradually dissipating rumble of thunder is caused by the time delay of sound coming from different portions of a long stroke.

1.2.4 Types of lightning

Currently there are few number of major lightning types have been recognized based on particular characteristics exhibits by each types of lightning strokes. Cloud to Ground, Inter Clouds, Intra Clouds and Cloud to Space are few major types of them (See figure 1.2). In addition, there are few minor types were also recognized called Dry lightning, Rocket lightning, Positive lightning, Ball lightning and Upper-atmospheric lightning.

1.2.5 Frequency of occurrence of lightning

The frequency of occurrence of lightning is basically defined as the flashers occurring per unit area per year. Due to the practical difficulties and necessity of very sophisticated equipment the frequency of occurrence of lightning is calculated by an alternative way by using an easily determined parameter called Keraunic level. This Keraunic level is defined as "the number of days in the year on which thunder is heard" [3]. It does not even distinguished between whether lightning was heard only once during the day or whether there was a long thunderstorm. Fortunately, it has been found by experience that the Keraunic level is linearly related to the number of flashers per unit area per year [3].

1.3 Lightning data of Sri Lanka

In 1968, there was a study called "lightning conditions in Ceylon, and measures to reduce damage to electrical equipment" which was carried out by Dr. Gi-ichi Ikeda by an Asian Productivity Project TES/68 [3]. In that study he has compiled the weather reports from 1931 to 1960 to generate the Isokeraunic Levels (IKL) as shown in the Figure 1.4 [5].

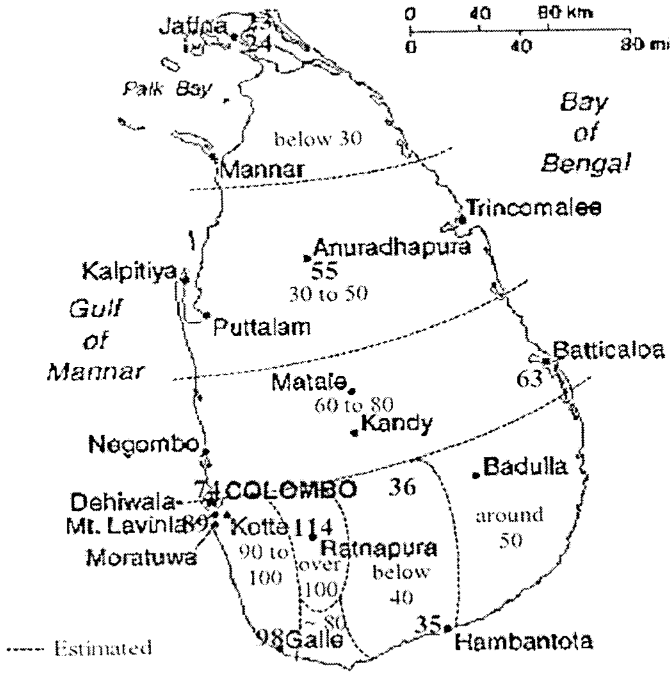

Figure 1.4 – Isokeraunic Level (IKL) map of Sri Lanka [5]

1.4 Introduction to transmission system of Sri Lanka

The power transmission system of Sri Lanka is solely owned and controlled by the Ceylon Electricity Board of Sri Lanka and presently comprises only 132kV and 220kV transmission lines interconnecting grid substations and power stations.

In early 1960s, the 132kV transmission lines were introduced with the development of Laxapana cascaded hydro power complex associated with Kehelgamu-Oya and Maskeli-Oya river basins. Similarly the 220kV transmission lines were introduced to the system in 1980s with the development of Mahaweli Hydro Power complex associated with the Mahaweli river basins. Subsequent developments in the transmission system have expanded the network in to the present state as shown in Annex-1 and Annex-2. Presently there are about 76nos. of transmission lines operating in the network connecting about 75nos. of transmission network points including power stations. The transmission network is presently controlled by the System Controlled Centre located at Dematagoda.

1.5 Lightning effects on power transmission lines

When charged clouds formed above a transmission line, causes to induce positive charges on shield wires as well as on phase conductors due to the negative charges at the bottom of clouds as shown in figure 1.5. This leads to form capacitances between

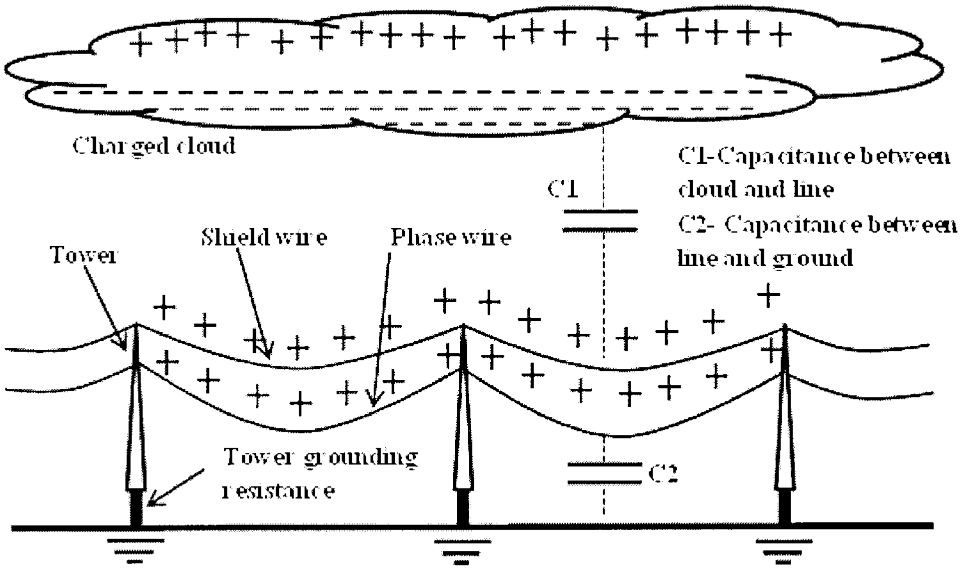

Figure 1.5 – Induced charges on a power transmission line

cloud to line, cloud to ground and line to ground; those will exist until the charge at cloud disappears by a lightning stroke. There are several discharging paths existing for these capacitors depending on the lighting stroke behavior and ultimately causing great damages and line interruptions.

There are three major possibilities of lighting stroke behavior causing line interruptions.

Case 1:

When a lightning leader strokes on to a tower or shield wire will discharges the capacitance between clouds to shield wire. This leads to flow heavy surge currents through towers to ground and casing tower potential rise in association with high grounding impedance of towers. Potential rise in towers induces extremely high stresses across line insulators which lead to flashover from tower to phase/line conductors called back flashovers.

Case 2:

When a lightning leader strokes on to a line/phase conductor (called as shielding failures), will induces very high voltages due to the direct discharge of capacitance between cloud to line/phase conductors. Basically the travelling waves will be generated on the line and causing high voltage stresses across the line insulation leads to breakdown at even low currents. The insulation failure is usually occurs at line insulators at towers whereas flashovers between phase/line conductors at mid spans are very rear.

Case 3:

When a lightning leader strokes to nearby ground directly or through any other grounded object, the capacitance between the cloud and ground will be discharged. Thereby the induced charges at towers and all other conductors will be discharged while forming travelling waves on conductors. In addition there is a possibility of potential rise on towers at close proximity of the lightning struck points due to the ground potential gradients formed by the lightning stroke. Thereby voltages will be appeared across insulators due to those combined actions of travelling waves and potential rise on towers leads to flashovers. Anyhow the flashover incidents of this kind is very rare and not a considerable fact in transmission system voltages higher than 66kV [3].

Parameter	Minimum	Typical	Maximum
Number of return strokes per flash	1	2 to 4	26
Duration of flash (s)	0.03	0.2	2
Time between strokes (ms)	3	40 to 60	100
Peak current per return stroke (kA)	1	10 to 20	250
Charge per flash (C)	1	15 to 20	400
Time to peak current (μs)	<0.5	1.5 to 2	30
Rate of rise (kA/μs)	<1	20	210
Time to half value (μs)	10	40 to 50	250
Duration of continuing current (ms)	50	150	500
Peak continuing current (A)	30	150	1600
Charge in continuing current (C)	3	25	330

Table 1.1 – Range of values for lightning parameters [6]

1.6 Lightning Parameters

There are several lightning parameters (See Table 1.1) of primary interest to the electric power utility engineer are defined and used to address the lightning issues as described in the previous section. Some of them are described in the following sections.

1.6.1 The quantity of lightning activity in a given area

The quantity of lightning activity is ideally measured in terms of the number of lightning flashes per unit area per year, called the Ground Flash Density (GFD). This value, denoted as N_g, is in units of flashes per km^2 per year. Today, the GFD is usually measured by use of lightning location systems, either by gated wideband magnetic direction-finding systems or time-of-arrival systems. Before using these advanced systems the GFD is calculated with the aid of local IKL data. The IEEE and CIGRE recommend a rough relationship of GFD and local IKL as shown in the equation 1-1 below [6].

$$GFD = 0.04\ T_d^{1.25} = 0.054\ T_h^{1.1} \quad (1\text{-}1)$$

Where:

GFD = average flashes to earth/km2/year

T_d = average thunder days per year (keraunic level)

T_h = average thunder hours per year (keraunic level)

1.6.2 The distribution of the crest current of a lightning flash

A primary database for lightning parameters was initially developed by Professor Karl Berger in Switzerland based on the number of strokes recorded on 70m and 80m high masts, located on top of the 650m high Mount San Salvatore. There were 1196 flashes in 11 years. Out of these, 75% were negative-upward, 11% were negative-downward, and the remainder was positive-upward [6]. These data was used in combination with some other recorded data at different countries to form the well know CIGRE crest current distribution curve. In addition to the CIGRE distribution cure there was a another equation formulated to obtain the crest current distribution curve by Anderson [6] and adopted by the IEEE/PES Working Group on Estimating the Lightning Performance of Transmission Lines.

Both these curves give almost the same distribution with deviations at very low and very high currents where the available lighting data is minimum (See figure 1.6).

1.6.3 The wave shape of a lightning flash

Almost all lightning strokes are different from each other and therefore no two stroke current wave shapes are exactly alike, and the variations in wave shape are substantial. Most computer programs that calculate line lightning performance assume a straight rising front, a double exponential wave shape, or a CIGRÉ wave shape.

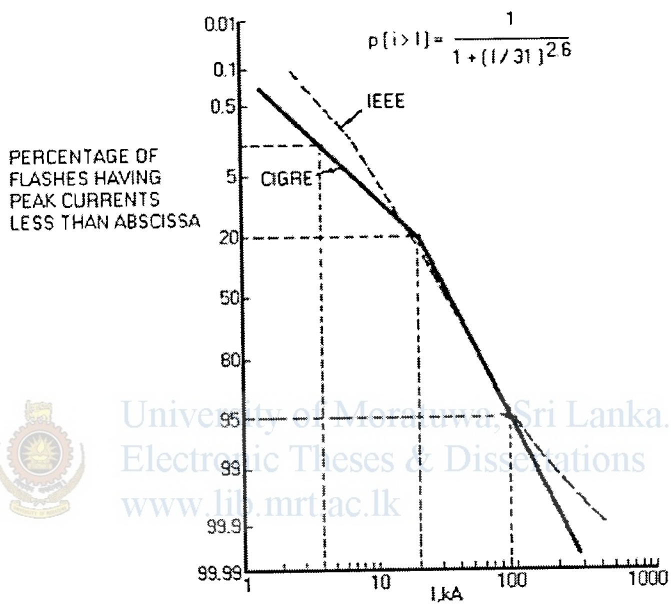

Figure 1.6 – Lightning Stroke Current Probability Distribution [6]

There is no exact rule for the use of a wave shape for EMTP simulations and the selection is depending on the type of EMTP analysis or the application. The front time, tail time, peak current magnitude and the total charge delivered by the stroke current are the basic parameters govern by the wave shape.

1.6.4 Total charge delivered by a lightning stroke

An approximated estimate of total charge delivered by a lightning stroke can be obtained by integrating its current waveform. By this integration results, it clearly shows that higher potion of the total charge delivered is associated with the tail side of the waveform rather at the front of it after the crest current is reached. Therefore the tail time of a lightning current stroke is the governing fact which determines the total charge delivery. Also the total charge in a lightning flash that determines the energy fed into surge arresters, and it is also the charge that causes pitting and burning of shield wires at contact points. It has been noted that, between some stroke current peaks and at the current decay at the end of lightning flashes, a low, almost direct current, can flow for many milliseconds; more charge can be delivered by this low current than by the high current peaks in a flash. These low currents, because of their longer duration, act somewhat like an arc welder. Continuing currents of hundreds of amperes lasting hundreds of milliseconds have been measured on instrumented towers. These continuing currents can transfer many coulombs of charge in addition to the main portion of the lightning wave shape [6].

Berger [6] integrated the current records of downward flashes to Monte San Salvatore in Switzerland to determine the charges delivered and reported that in one case a positive charge reached 300 coulombs. The positive flashes tend to deliver almost 10 times as much charge as negative flashes, but positive flashes are much less frequent [6].

1.7 Selected transmission line for the study

The case study described in this report is based on the 220kV power transmission line which connects Kotmale Generation Station to Biyagama Grid Substation as shown in the figure 1.7.

This transmission line was commissioned in 1985 as a part of the transmission line project which consists of constructing the 220kV duplex zebra conductor line from

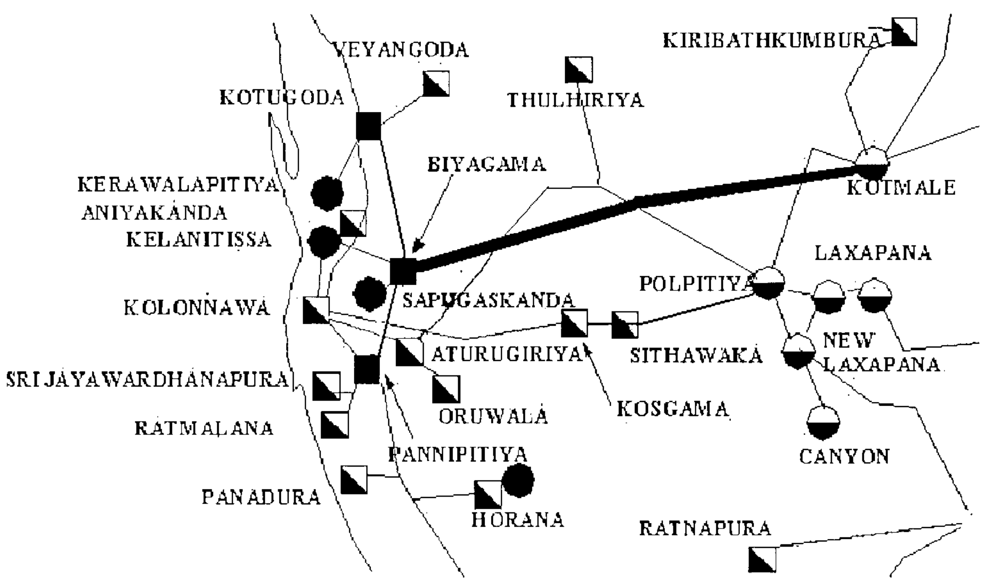

Figure 1.7 – 220kV, Biyagama-Kotmale Transmission Line

Victoria to Biyagama through Kotmale as shown in the figure 1.8.

The transmission line selected in this study is about 70.5km in length and having 206 nos. of double circuit steel lattice towers with 2nos. Galvanized Steel overhead Ground Wires providing protection against lightning. A complete set of line data is attached as Annex 3.

The selected Biyagama-Kotmale 220kV transmission line is one of the critical transmission network elements in the national grid because; this line delivers the highest portion of the generated power from Mahaweli hydro power complex to the loads.

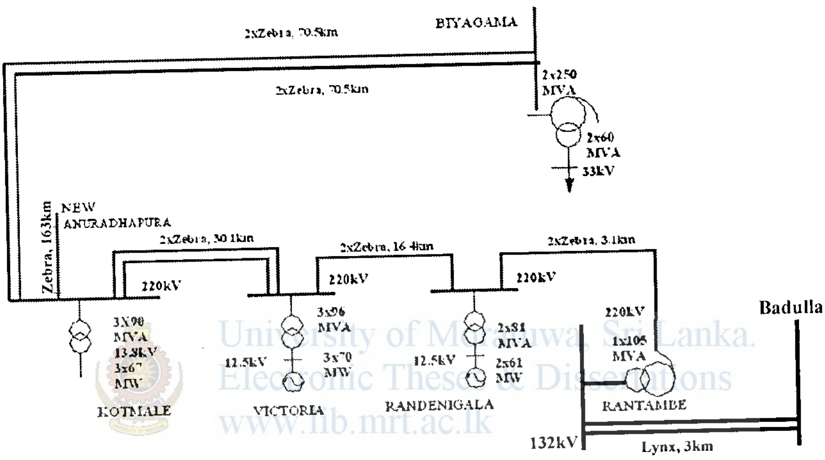

Figure 1.8 – Single line diagram of Victoria complex with Biyagama-Kotmale line

1.7.1 Transmission Towers and configuration

As described in the previous section the selected transmission line consists of 206nos. double circuit, self-standing, steel lattice towers with standard 3m, 6m, 9m and 12m body extensions at some certain locations to maintain the minimum ground clearance value of 7.31m. Therefore the typical tower height will vary between 30 to 35m. Conductor arrangement at towers is in vertical formation where each cross arm holds 02nos. Zebra conductors for each phase. A typical tower drawing is attached as Annex 4.

1.7.2 Insulators and arc horn gaps

Toughen glass Cap & Pin type insulator discs along with galvanized insulator hardware are used to form both suspension and tension insulator strings. Each line insulator string of this transmission line is consists of an arc horn gap where the gap is adjustable at line termination ends only. The gap of arcing horn for a 220kV line is set to be 2m whereas the gap at termination ends will be adjusted as per the insulation coordination requirements of the substation equipment. CEB specification for a single insulator disc is given in Table 1.2.

1.7.3 Phase conductors

Duplex Zebra conductors of 484mm^2 are used for the phase conductors of the selected transmission line having maximum operating temperature at 75^{0}C. As a result the corona performance of the line is better than other available transmission lines due to the increased Geometrical Mean Radius of the conductors. Anyhow the increased corona performance of phase conductors has a negative impact on transient performance due to the reduction of travelling wave-front distortion leads to develop comparatively higher voltages across line insulators.

Dimensions	Units	Suspension string	Tension string
Nominal diameter of disc	mm	254	280
Nominal spacing of disc	mm	146	146
Nominal creepage distance	mm	280	300
Withstand voltages			
Power frequency, Dry	kV	70	70
Power frequency, Wet	kV	40	40
Impulse 1.2x50uS	kV	110	110
Puncture voltage	kV	110	110
Electro mechanical failure load	kN	120	160

Table 1.2 – CEB Specifications for a single insulator disc [4]

1.7.4 Earthing of towers

Earthing of towers is of great importance due to its direct impact on line performance at lightning events. Most of the tower earthing has been done through the tower foundation where a strip of metal bonded to the tower leg is taken out and earth separately. Very low earth resistances in the order of 2Ω to 3Ω are obtained where insitu or precast pile foundations used in marshy soil conditions.

Achieving of CEB specified 10Ω earthing resistance is of great difficulty in the areas where the towers are located in rocky lands or gravel soil conditions. In such cases counterpoise wires were used with specified lengths. Figure 1.9 shows the variation of earthing resistances of selected two line sections having tower numbers 31-52 and 83-97 starting from Kotmale end.

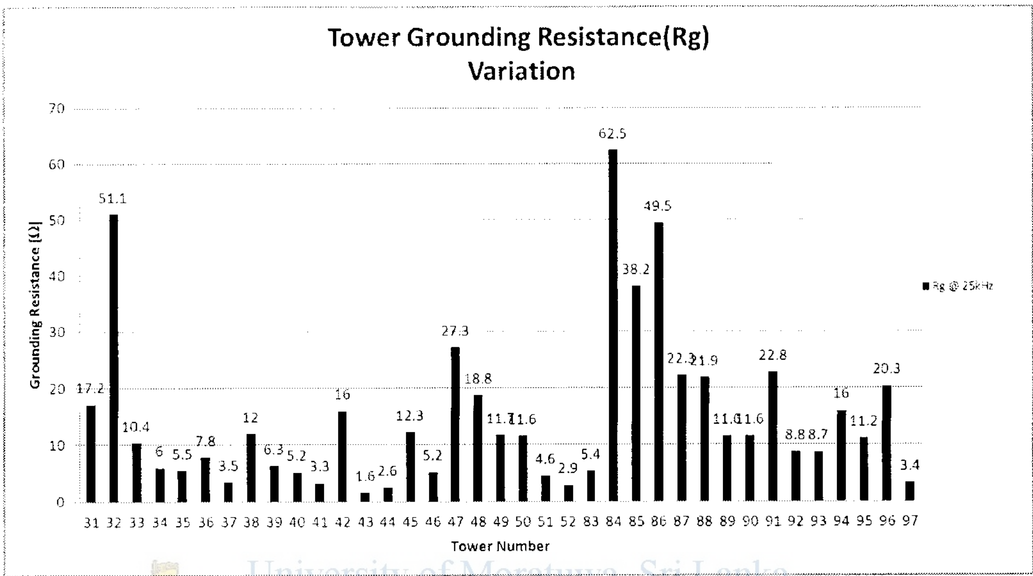

Figure 1.9 – Grounding resistance variation of towers 31-52 and 83-97 starting from Kotmale end