Professor R. H. Paul Commemoration Lecture 1994

COST - EFFECTIVE INSULATION THROUGH PROPER CO-ORDINATION

by

Prof. J. Rohan Lucas

BScEng, MSc, PhD, FIEE, CEng, FIE(SL), MCS(SL),

Professor in Electrical Engineering, University of Moratuwa

Mr. Chairman, Fellow Engineers, Ladies and Gentlemen.

It gives me great pleasure to deliver this Oration, and I thank the Institution of Engineers, Sri Lanka and in particular its Electrical Sectional Committee, for inviting me to deliver the R.H. Paul Commemoration Lecture for this year. It was with a lot of apprehension that I accepted the invitation to pay this annual tribute.

I had the privilege of being taught by Professor R.H. Paul towards the tail end of his illustrious career. He retired from the post of Professor of Electrical Engineering while I was still an undergraduate at the Engineering Faculty of the University of Ceylon, at Peradeniya.

Fortunately for me he devoted his time to teach us till the end of our course in both theory and practicals even though he had by then retired. On account of his retirement, I did not get the opportunity of moving very closely with him and working with him at the University after my graduation. However I was very fortunate to get to know him a little while serving as a co-opted Associate Member representative on the same IEE (Ceylon Overseas Branch) Committee, on which Professor Paul was actively participating.

I believe that not many of you here today, has had the good fortune to have come under his direct influence, and some of you may even not be aware of the contributions he has made to Electrical Engineering in this Country. Thus I believe that I must first talk a little about Professor Paul before I embark on the technical content of my lecture.

Professor R.H. Paul

Professor Robert Hoisington Paul, is considered as the **Father of Electrical Engineering Education in Sri Lanka** and aptly deserves the title.

R.H. Paul having excelled in studies at the University College (the predecessor of the University of Ceylon) won the Government Scholarship in 1924 to study in the United Kingdom. He obtained a First Class Mechanical Sciences Tripos degree from the University of Cambridge and thereafter served as a graduate apprenticeship at the Metropolitan Vickers Co. He returned to Ceylon in 1930 and joined the Ceylon Technical College as a Lecturer.

In the nineteen forties, courses for the external degrees in Engineering of the University of London was commenced in Colombo, and R.H. Paul was promoted as the first Professor of Electrical Engineering. Professor Paul had the task of establishing, for the first time in Sri Lanka, teaching and laboratory facilities to meet the rigid standards of the University of London. He was mainly responsible for getting the recognition of the University of London for the Technical College to prepare students for its Bachelor of Science in Engineering degree. He served with great distinction the post of Professor of Electrical Engineering which he held for 18 years.

He was President of the Institute of Engineers, Ceylon in 1968, and I believe the first Ceylonese Overseas Representative of the Institution of Electrical Engineers, London. Even after his retirement he took a great interest in the professional activities of the IEE (Ceylon Overseas Centre) until his death in 1978.

Professor Paul has taught us, amongst many other things, that it is vital that power engineers should, by keeping outages to a minimum, maintain a reliable and continuous supply of electricity. It is also imperative that such a system should be cost effective. It is therefore necessary to pay special attention towards proper co-ordination of the system components. Protecting the transmission system from damages due to faults and overvoltages due to lightning and switching are among them.

As a tribute to this great teacher I have thus selected Co-ordination and in particular that of the proper co-ordination of insulation, as the subject for my oration.

Co-ordination

Co-ordination is the process of establishing the relationship among two or more sub-activities or sub-systems in order to achieve desired goals with optimisation of costs and benefits. Absence of co-ordination will invariably result in the sub-optimisation and possibly waste. Thus co-ordination is an important aspect in almost all engineering in preventing failures. Reliability and Cost are the two main factors that are considered. It is not always economical to make sure that failure does not arise under the highest stresses that may occur. However, safety cannot be compromised, although failure of equipment can be tolerated. The designer must place a limit at the point at which the cost of achieving a further improvement in reliability cannot be justified by the savings the reduced breakdowns may bring. Also the cost of the unserved service cannot be readily assessed in money terms. Thus the design philosophies may not always be the same from problem to problem.

The following example makes this point somewhat clear. The Highway engineer who designs a bridge or the Structural engineer who designs a building, has to make sure that these structures do not collapse under stresses caused by all foreseeable and even catastrophic situations. He cannot afford to design cost-effective houses such that one house in hundred will collapse every year killing its occupants. This is because life is precious and we cannot give a monetary value to the human life. On the other hand, the philosophy in designing the protection of equipment against damage by faults and surges can be completely different. It is definitely not economically feasible to prevent some form of breakdown due to all foreseeable stresses. The design philosophy adopted is that when a breakdown is inevitable, it is confined to locations where they cause the minimum damage, minimum interruptions and the least costly to repair.

For example, in the domestic installation, we provide co-ordinated fuses (or miniature circuit breakers) from the main switch, through the consumer unit to the final circuit. This is done so that a fault in an equipment in the final circuit will cause only that circuit to be disconnected, without interruption to the supply to all other circuits. The fuse is provided such that failure occurs at this point, and does not cause the equipment to get damaged. If proper co-ordination of the fuses were not provided, the fuse at the main switch could burn instead of in the individual circuit, causing all the circuits to be interrupted. Of course, it may also be possible to design all equipment such that they can withstand all foreseeable magnitudes of fault currents without disruption. However, even if it were possible, it would make the cost of all equipment unbearably high.

The same philosophy is used in the design of insulation. In fact the power system insulation is based on a statistically acceptable level of failure, rather than on a no failure basis for all foreseeable magnitudes of surges.

However, the following must be borne in mind. A large category of real life engineering problems are inherently ill defined. Constants required in estimation are rarely known precisely and are often not even really constant. The driving functions are difficult to describe mathematically, and the output only depictable statistically. Estimating lightning performance of transmission lines is such an example. Lightning flash characteristic and flash locations on a transmission line vary not only from line to line but can vary widely from year to year, and even within an year (rainy season, dry season etc.). Even the tower footing resistance of a given tower is not a constant but varies with current and time. It is thus pointless and misleading to use a prediction accuracy far exceeding the precision of the knowledge of the constant. Quite often, to cater for unknown parameters, it becomes necessary to apply an estimated and thus inaccurate safety factor to results which have been obtained from an expensive large-scale overvoltage calculation. This is a contradiction in itself. Thus in some cases simple procedures to co-ordinate equipment are in fact better and much more economical. Also, beside the fact that the overhead line may be situated in an area with a lightning activity substantially different from the average, there is a large difference between the assumption of randomness that may sometimes be made. This can be easily understood by the following extreme case. A ground flash density of 4 (that is 4 flashes/km^2 every three months, or, if we make an assumption of accumulation, it could even be said to give 40 flashes/km^2 in 1 hour but once every 10 years. Obviously the second assumption although giving the same ground flash density would be an absurd one to make.

Taking all the above into consideration, the philosophy adopted in insulation co-ordination can be stated simply as follows. It is much more economical to allow for the possible damage of one transformer, in perhaps a hundred per year, than doubling or trebling the cost of each of the (hundred) transformers to reduce the failure rate to a lower value. In fact even under this circumstance it may not possible to avoid all possible failures.

This design philosophy is the modern day insulation co-ordination. I hope to restrict the remainder of my talk initially to describing some details of insulation co-ordination and then go on to its application to the power system in Sri Lanka.

Insulation Co-ordination

Insulation Co-ordination was originally defined to be the arrangement of the insulation levels of the many components in the power system. It was done in such a manner that if a failure of the insulation were to happen, it would occur in the following manner. (i) It would be localised to such parts of the system where it would result in the least damage; (ii) it would be the least expensive to repair; and (iii) it would cause the least disturbance to the continuity of the supply.

The present usage of the term is broader. It is defined in the IEC Publication 71-1 on Insulation Co-ordination as follows. "Insulation co-ordination comprises the selection of the electric strength of equipment and its application, in relation to the voltages which can appear on the system for which the equipment is intended and taking into account the characteristics of available protective devices, so as to reduce to an economically and operationally acceptable level the probability that the resulting voltage stresses imposed on the equipment will cause damage to equipment insulation or affect continuity of service".

The overall aim is thus to reduce to an economically and operationally acceptable level of risk the cost and disturbance caused by insulation failure and resulting system outages.

Conventional method of insulation co-ordination

In the conventional method of insulation co-ordination, in order to avoid insulation failure, the insulation level of the different types of equipment connected to the system are selected to be higher than the magnitude of transient overvoltages that appear on the system. On many transmission lines, lightning is the main cause of unscheduled supply interruptions, as they produce transient overvoltages.

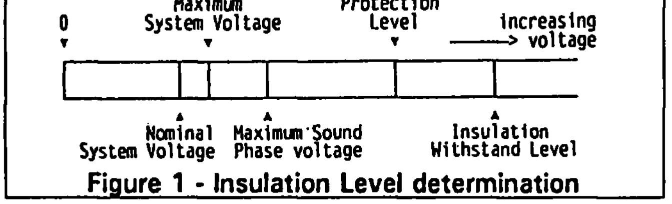

Figure 1 - Insulation Level determination

The magnitude of transient over-voltages are usually limited to a protective level by protective devices such as spark gaps and lightning arrestors. Figure 1 shows how this is done in the conventional procedure. The maximum system voltage is normally about 10% higher than the nominal voltage. Depending on the type of earthing, the maximum voltage on the healthy phases during a fault would be still higher. In order to prevent unnecessary interruptions, the protection level of the protective device must be still higher than this value. In order to prevent damage to the insulation, the lightning impulse withstand level has to be above the protective level by a safe margin of 15 - 25%.

Statistical Method of Insulation Co-ordination

For system voltages up to about 300 KV, damages due to overvoltage is mainly due to lightning. The cumulative distribution of lightning stroke currents is shown in figure 2.

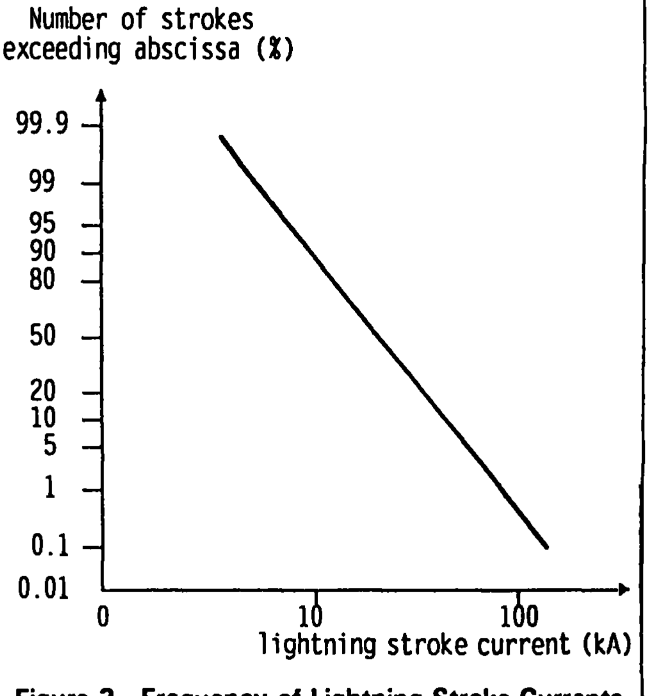

Figure 2 - Frequency of Lightning Stroke Currents

It shows that lightning currents in excess of 100 kA is possible, but that the probability of exceeding it is extremely small.

Especially for the higher system voltages, the simple approach used above is inadequate. Economic factors dictate that insulation co-ordination be placed on a more scientific basis. This is the statistical method.

As the transmission voltages increase, the insulation and the clearances in air do not increase linearly with voltage but approximately to $V^{1.6}$. Thus, while it may be economically feasible to protect the lower voltage lines up to an overvoltage factor of 3.5 (say), it is definitely not economically feasible to have an overvoltage factor of more than about 2.0 or 2.5 on the higher voltage lines.

The statistical procedure acknowledges the fact that insulation failures may occur, and attempts to quantify the risk of failure and to use it as a safety index in insulation design. The statistical approach is particularly valuable where there is a strong economic incentive towards a reduction of the insulation strength especially when switching overvoltages are a problem.

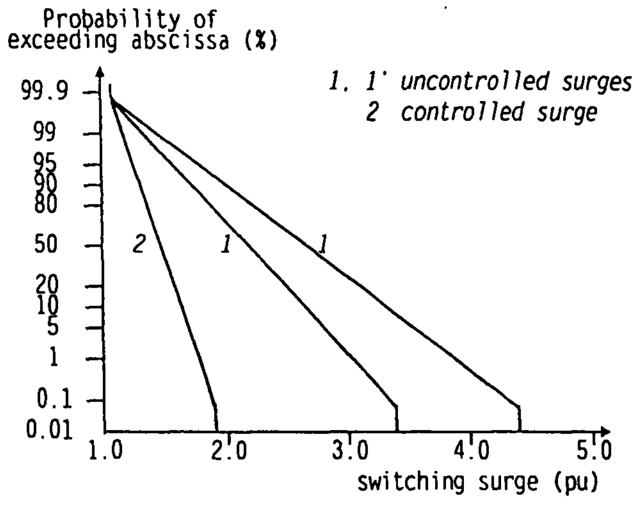

Figure 3 - Distribution of switching overvoltages

In a statistical study, what has to be known is not the highest overvoltage possible, but the statistical distribution of overvoltages. The switching overvoltage probability in a typical line is shown in figure 3.

It is seen from this figure that the probability of overvoltage decreases very rapidly. Thus it is not economic to provide insulation above a certain overvoltage value. In practice, the overvoltage distribution characteristic is modified by the use of switching resistors which damp out the switching overvoltages, or by the use of surge diverters set to operate on the higher switching overvoltages. In such cases, the failure probability would be extremely low.

Evaluation of Risk Factor

The aim of statistical methods is to quantify the risk of failure of insulation through numerical analysis of the statistical nature of the overvoltage magnitudes and of electrical withstand strength of insulation.

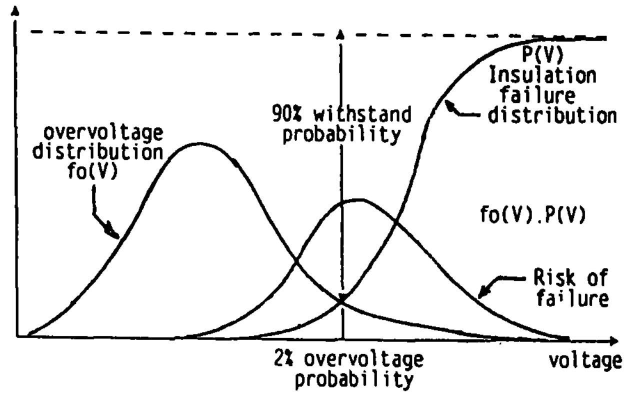

Figure 4 - Evaluation of risk factor

For this we need to know the probability of the overvoltage distribution that can occur in the system, and the insulation withstand distribution of the equipment protected.

We cannot economically find suitable insulation such that the withstand distribution does not overlap even to the slightest extent with the overvoltage distribution. Thus in the statistical method of analysis the insulation is selected such that the 2% overvoltage probability in the system coincides with the 90% withstand probability of the equipment as shown in figure 4. The risk of failure of the insulation is then dependant on the area of the product curve of the overvoltage distribution function fo(V) and the probability of insulation failure P(V).

Breakdown of Oil in Liquid/Solid Insulation

Insulation co-ordination does not simply mean the comparison of dielectric strength of insulation without consideration of the voltage stresses. This can be best understood by considering the case of transformer board used together with oil.

The general concept of breakdown of insulating oils when used in equipment such as transformers is questionable in practice. Even new oil has a certain possibility of breaking down even at low voltages due to the formation of bridges by foreign particles. This is due to the high possibility of fibre particles which may detach from paper, wood etc.

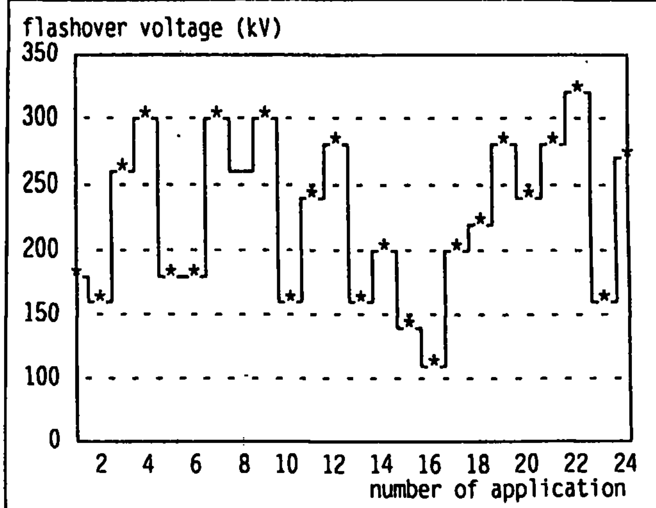

Figure 5 - Electric Strength of Oil/Board Surface

In fact Robinson et Al have experimentally shown (Figure 5) that a ratio as high as 2.7 can exist between the highest and lowest flashover voltages, even though no oil degradation has taken place between readings. Thus for insulation systems immersed in oil, it is essential to consider the statistical nature of their breakdown strength, rather than just the average value.

Another misconception in insulation co-ordination is the combined use of solid insulation, such as transformer board with oil. Solid insulating materials generally have a much higher electrical breakdown strength than insulating oil. This may sometimes misguide the practising engineer into believing that by using thicker solid insulation barriers, in already existing oil insulated equipment, would give a better overall insulating performance. This is not true, and in general would lead to a poorer overall insulation. This is because of the differences in the relative permittivities of the solid and liquid insulating materials. The mismatch in the relative permittivity between the various insulating materials used in transformer construction will lead to stress concentration in those with lower relative permittivity.

The following example illustrates this point. For transformer board [$\varepsilon_1 = 4.4$, ξ_{max} 48 kV/mm] and for insulating oil [$\varepsilon_2 = 2.2$, ξ_{max} 12 kV/mm]. Thus a gap of 10mm separated by transformer board would be able to withstand a critical voltage of about 480 kV, whereas a similar gap in oil would be able to withstand 120 kV. It can be shown both theoretically and practically that the insertion of a solid insulation (transformer board) into this system will not improve the voltage withstanding capacity as expected. For the combined system, the total voltage that can be applied, with a 2mm thick transformer board keeping the total clearance the same, is only 108 kV. If we further increase the thickness of the transformer board to 5mm, the value decreases further to 90 kV. This value keeps on decreasing until the thickness of the transformer board approaches the full thickness of 10mm. At this limiting value, with a thin film of oil, the maximum critical voltage that can be applied is only 60 kV. Thus it is seen that liquid\solid insulation should be selected with care. However it is to be remembered that with the presence of a number of thin barriers an overall advantage will be gained as the probability of formation of bridges is reduced as the oil is compartmentalised.

Let us now consider some aspects of co-ordination of external insulation.

Length of Overhead Shielding Wire

For reasons of economics, the same degree of protection is not provided throughout a transmission line. Generally, it is found sufficient to provide complete protection against direct strikes only on a short length of line prior to the substation. When the surge magnitude exceeds the critical voltage, corona would occur, distorting the surge wavefront as it travels.

For insulation co-ordination, the deformation caused by corona is of the greatest importance. When a surge voltage wave, travelling on an overhead line, causes an electric field around it exceeding the critical stress of air, corona will be formed. This corona formation obviously extracts the energy required from the surge. Since the power associated with corona increases as the square of the excess voltage, the attenuation of the waveform will not be uniform so that the waveform gets distorted.

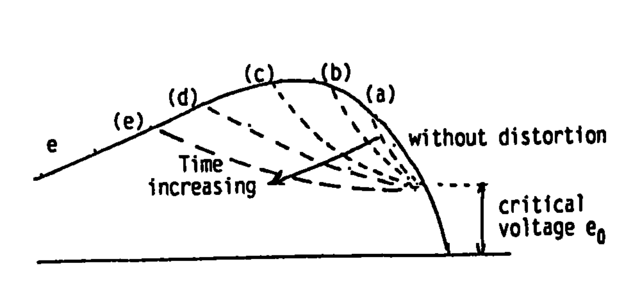

Figure 6 - Modification of waveshape due to corona

Corona increases the effective radius of the conductor giving rise to a greater capacitance for the outer layers. Since the line inductance remains virtually a constant, the surge associated with the outer layers of corona would have a lower wave velocity than in the conductor itself. These effects in practice give rise to a wavefront distortion, as shown in figure 6. Corona thus reduces the steepness of the wavefront above the critical voltage, as the surge travels down the line, and also loses energy to the atmosphere. The stresses thus caused on terminal equipment connected at substation end of the line is thus greatly reduced. The minimum length of earth wire should be chosen such that in traversing that length, all voltage elements above the maximum surge level that can be withstood at the terminal has been distorted by corona.

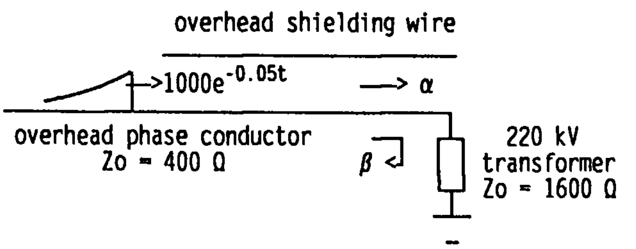

Figure 7 - Example of earth wire shielding

It can be shown that for a typical 220 kV transformer (figure 7) having an impulse insulation level 1050 kV, a length of about 2 km of earth wire would be required to give a sufficient margin of protection from direct lightning stroke with a peak value of 1000 kV, through attenuation due to corona. In the absence of the shielding wire the overvoltage could typically have risen to in excess of 1600 kV.

Surge Protection

An overhead earth wire provides considerable protection against direct strikes. They also reduce induced overvoltages. However, they do not provide protection against surges that may still reach the terminal equipment. Such protection may either be done by diverting the major part of the energy of the surge to earth (surge diverters), or by modifying the waveform to make it less harmful (surge modifiers). The insertion of a short length of cable between an overhead line and a terminal equipment is the commonest form of surge modifier as these cables are normally present for termination purposes. Spark gaps and surge arrestors are used to divert the surge.

Spark gaps for surge protection

The simplest and cheapest form of protection is the spark gap. The selected gap spacing should not only be capable of withstanding the highest normal power frequency voltage but should flash-over when overvoltages occur, protecting the equipment. However, this is not always possible due to the voltage-time characteristics of gaps and equipment having different shapes. Also, once a gap flashes over under a surge voltage, the ionised gap allows a power frequency follow through current, leading to a system outage.

When spark over occurs across a simple rod gap, the voltage suddenly collapses giving rise to a chopped wave. This chopped wave may sometimes be more onerous to a transformer than the original wave itself. Thus rod gaps are not generally used as the main form of protection in transmission.

Expulsion Tube Lightning Arrestor

An improvement to the simple spark gap is the expulsion tube arrestor which consists essentially of a spark gap arranged in a fibre tube, and another series external rod gap. A typical arrangement for a 33 kV expulsion tube, has an external gap of the order of 50 mm and the internal gap of about 180 mm. The power frequency follow current is interrupted within one or two half cycles so that protective relays would not operate causing unnecessary interruptions.

The expulsion gaps, which are comparatively cheap, are suitable for the protection of transmission line insulators and for the protection of rural distribution transformers, where other arrestors may be too expensive and rod gaps inadequate. However, they are unsuitable for the protection of expensive terminal equipment on account of their poor voltage-time characteristics.

Surge Diverters

Surge diverters (or lightning arrestors) generally consist of one or more spark gaps in series, together with one or more non-linear resistors in series. Silicon Carbide (SiC) was the material most often used in these non-linear resistor surge diverters. However, Zinc Oxide (ZnO) is being used in most modern day surge diverters on account of its superior volt-ampere characteristic. In fact the ZnO arrestor is now used gapless, as its normal follow current is negligibly small. Typical volt-ampere characterisitics of SiC and of ZnO non-linear elements are shown in figure 8 for comparison with that of a linear resistor.

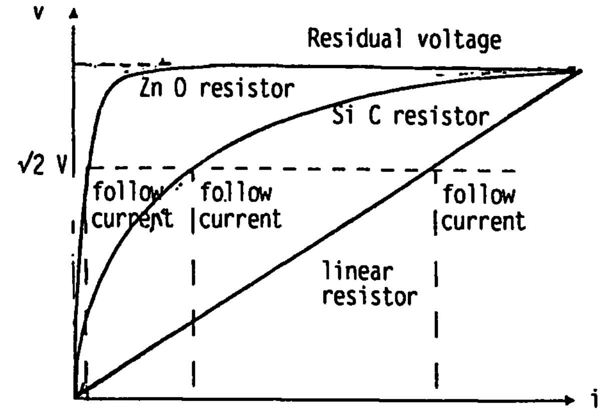

Figure 8 - Characteristics of arrestor elements

It is seen that while a large current is drawn under overvoltage condition in all three cases, the follow current is fairly large in the linear resistor, small in the SiC resistor, and negligibly small in the ZnO resistor. Their characteristics may be mathematically expressed as follows.

$v = k_1\ i$ for a linear resister

$v = k_2\ i^{0.2}$ for a SiC resister

$v = k_3\ i^{0.03}$ for a ZnO resister

Typically, if the current were to increase a 100 times, the corresponding increase in voltage would be 100 times for the linear resistor, 2.5 times for the SiC resistor, but only 1.15 times for the ZnO resistor. This means that for the same residual voltage and the same discharge current, the follow current would be (in the absence of a series gap) of **kA** for a linear resistor, **A** for a SiC resistor and just **mA** for a ZnO resistor.

When a surge appears at a surge diverter terminal, within a short time the breakdown voltage of the series gap is reached, and the arrestor discharges. Unlike in the rod gap, the voltage does not collapse to zero instantly due to the voltage across the non-linear resistor. When the surge voltage increases, there is a corresponding but rapid decrease of the resistance value, thus diverting the surge energy to earth. Once the surge passes through. the design is such that the power frequency voltage remaining is insufficient to maintain a sufficient current for the arc to continue. Thus the arcs extinguish and the gaps reseal. In the case of the ZnO arrestor, due to the negligible continuous power frequency current even in the absence of a series gap, the series gap is eliminated simplifying construction and resulting in the gapless arrestor.

Location of lightning arrestos

The best protection is obtained for terminal equipment by placing the arrestor as near as possible to that equipment. However, it is not feasible to locate an arrestor adjacent to each piece of equipment. Thus it is usually located adjacent to the transformer. However, where the insulation withstand level of the transformer permits, the arrestor may be located at a distance from the transformer to include other substation equipment within the protected zone. Thus it may be worth while considering installing them on the busbars themselves when permissible.

When arrestors must be separated from the protected equipment, additional voltage components are introduced, which add instant by instant to the discharge voltage due to reflections occurring.

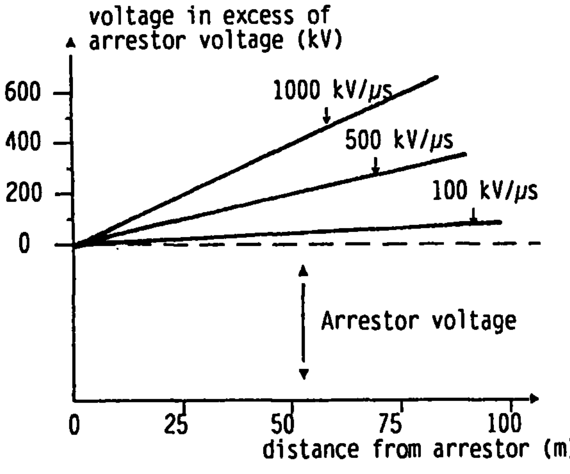

Figure 9 - Effect of separation on overvoltage

Figure 9 shows how the voltage at the terminal increases with separation for typical rates of rise.

For example, for a 220 kV transformer (BIL 1050 kV) protected from a 1300 kV steep fronted lightning wave (with a rate of rise 1200 kV/μs) by a lightning arrestor (protective level 560 kV), typically a separation of 50m from the transformer may be permissible for a protective margin for

25%. If the rate of rise were lower at 500 kV/μs, 100m would have been permissible.

Table I gives the characterisitics for station type lightning arrestors and table 2 gives typical separation distances permissible between arrestor location and transformer. For line type arrestors, the discharge voltages are 10 to 20% higher and the corresponding separation distances are roughly half.

When multiple lines meet at a busbar, the voltages transmitted are lower. It has been suggested that in the presence of multiple lines, the separation distances may be exceeded by about 9% for one additional line, 21% for two addition lines and 39% for three additional lines for the same degree of protection.

Protection of Open Circuit Breaker

Circuit breaker failures during thunderstorms seem to indicate that they may occur after a shielding failure flashover of the line insulation has been cleared by the breaker. For insulation co-ordination, such effects are important, since the open breaker situation may represent a very unfavourable condition, even if it is only temporary.

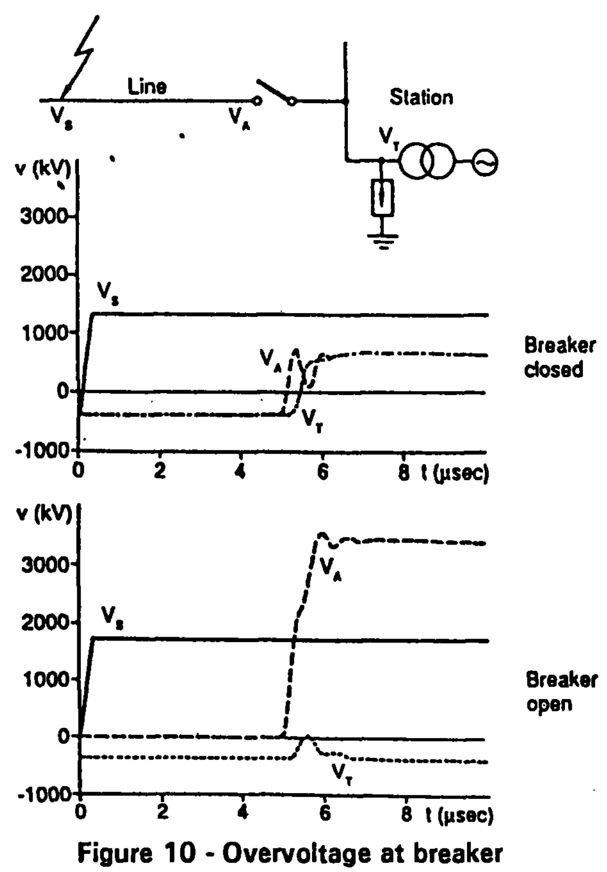

Figure 10 - Overvoltage at breaker (without additional protection)

During an opening of a circuit breaker due to a fault, such as to clear an arc caused by lightning across a co-ordinating gap on the transformer bushing, another surge may appear on the line. This is highly probable since in approximately 55% of cases lightning has multiple strokes. In this case, a lightning arrestor located on the equipment side of the circuit breaker has no effect. Thus if a line entrance arrestor is also not present, the full surge may appear across the circuit breaker before the breaker has fully recovered its dielectric strength across the contacts. Thus the circuit breaker is heavily stressed.

The presence of a co-ordinating gap on the line side of the breaker will also give poor protection, due to the delay in spark-over-on steep voltage surges and the high settings required to prevent unnecessary power frequency interruptions. On the other hand, the provision of an additional set of arrestors at the line entrance could be justified as the cost of the circuit breaker and the disruption to the supply caused by its loss is much more. Figure 10 shows a typical overvoltage build up for a lightning stroke on a 500 kV system in the absence of additional breaker protection.

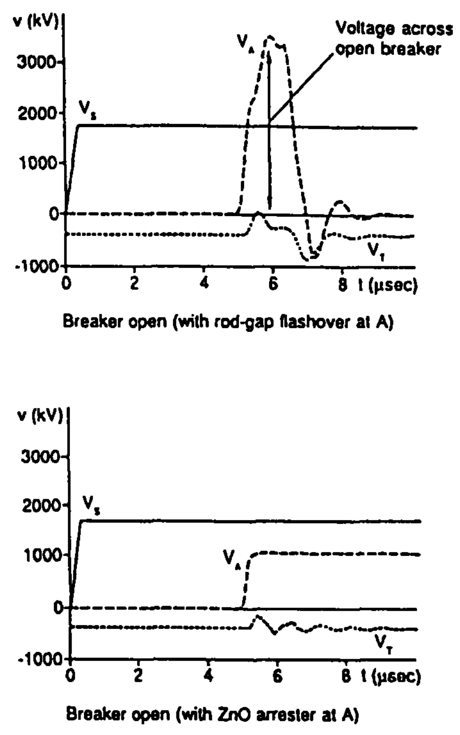

Figure 11 - Overvoltage at line breaker (with additional protection)

Figure 11 shows the corresponding situation when additional protection is given by a protective rod gap on the line side of the breaker and also the superior protection given by an additional arrestor on the line side. A remarkable improvement is seen with the ZnO arrestor.

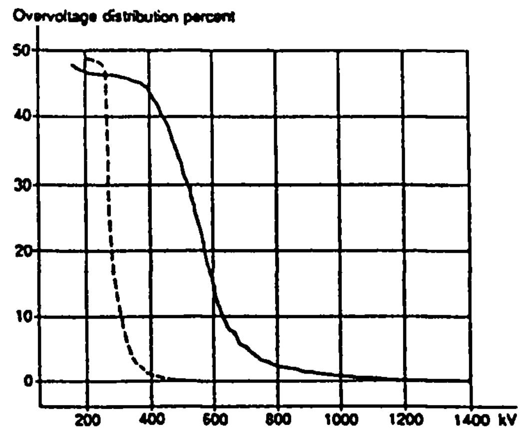

Figure 12 - Overvoltage distribution at breaker

Figure 12 shows the overvoltage distribution at the breaker with only one arrestor located at the transformer (50m behind the breaker), and as a comparison the dashed curve indicates the overvoltage distribution when an additional arrestor is installed 5m in front of the breaker.

Lightning Activity in Sri Lanka

The ground flash denisty of lightning activity is not easily measured. However, the keraunic level (or number of thunderstorm days) is obtained much more readily. The only study, to my knowledge carried out in Sri Lanka is that of Ikeda. He has obtained the keraunic levels at about 10 locations around the island for the period 1930 - 1960. He has also found that the keraunic level in the lowlands of Sri Lanka (less than about 100m above sea level) has an almost linear relationship to rainfall (figure 13) and to the number of rainy days (figure 14).

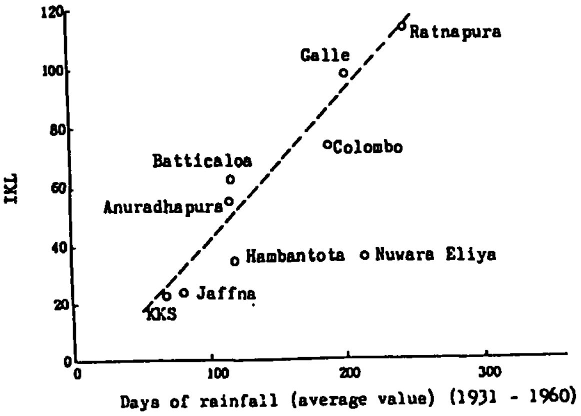

Figure 13 - Days of Rainfall

With this he has constructed an Isokeraunic level map for Sri Lanka (Figure 15). Figure 16 gives the average rainfall map of Sri Lanka for comparison.

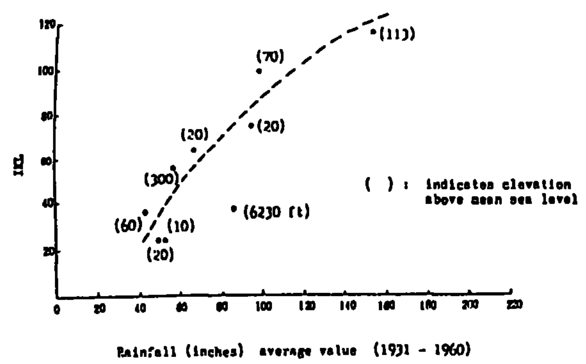

Figure 14 - Quantity of Rainfall

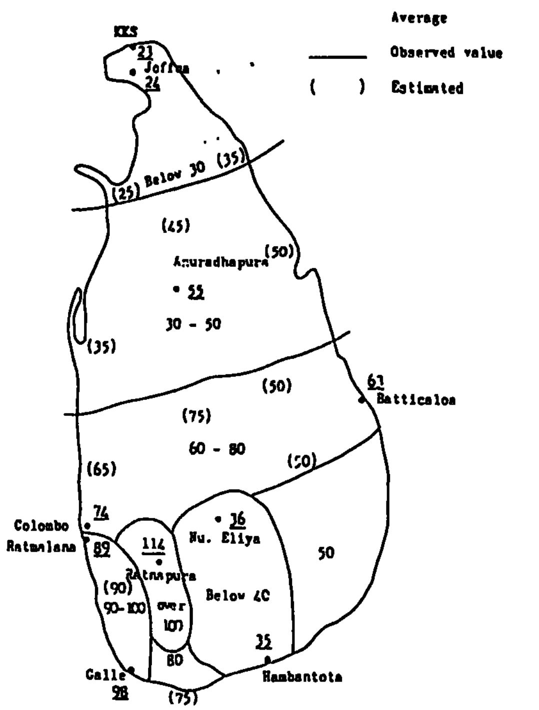

Figure 15 - Isokeraunic Level Map of Sri Lanka (Ikeda)

Ikeda has also shown a good correlation between the number of damaged transformers during any month and the average monthly keraunic level in Sri Lanka, as shown in figure 17.

The monthly variation of the ESDD (equivalent salt deposit density) measurements in Sri Lanka has been obtained by the Ceylon Electricity Board around 1988 (Figure 18). It shows a significant increase of pollution levels near the sea cost (up to about 400m inland). The level is seen to be almost ten times that elsewhere. Beyond 800m, there is no significant change from average level.

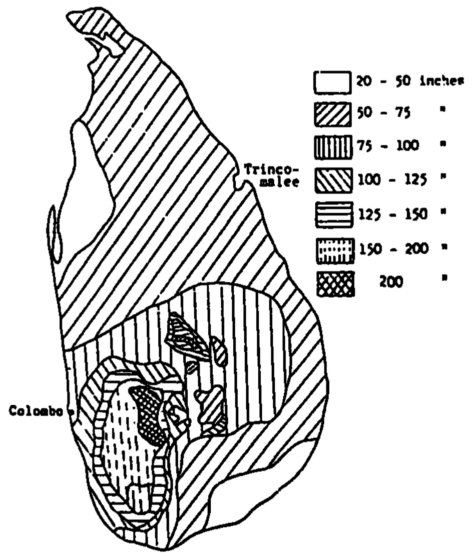

Figure 16 - Annual Average Rainfall Map of Sri Lanka

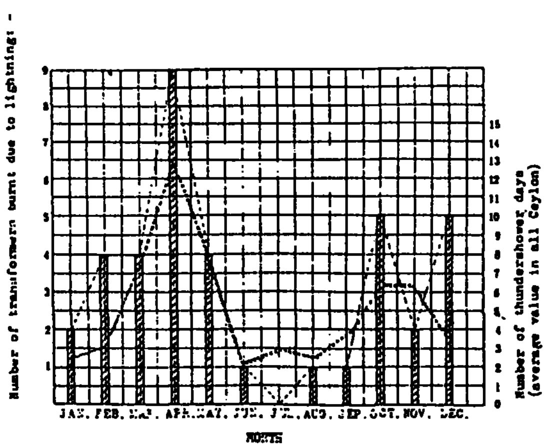

Figure 17 - Monthly distribution of damaged transformers & Keraunic level

Line Insulation

Line insulation in transmission lines is basically provided by suspension insulator units. Suspension units perform two basic functions. They provide both the mechanical support for the conductors, and electrical insulation and clearances from earth. Both these functions must be performed continuously throughout the entire operating life. To achieve the high level of reliability required from modern transmission lines, the insulators must be designed to prevent failure by puncture, to avoid unnecessary flashovers, and to keep its mechanical strength.

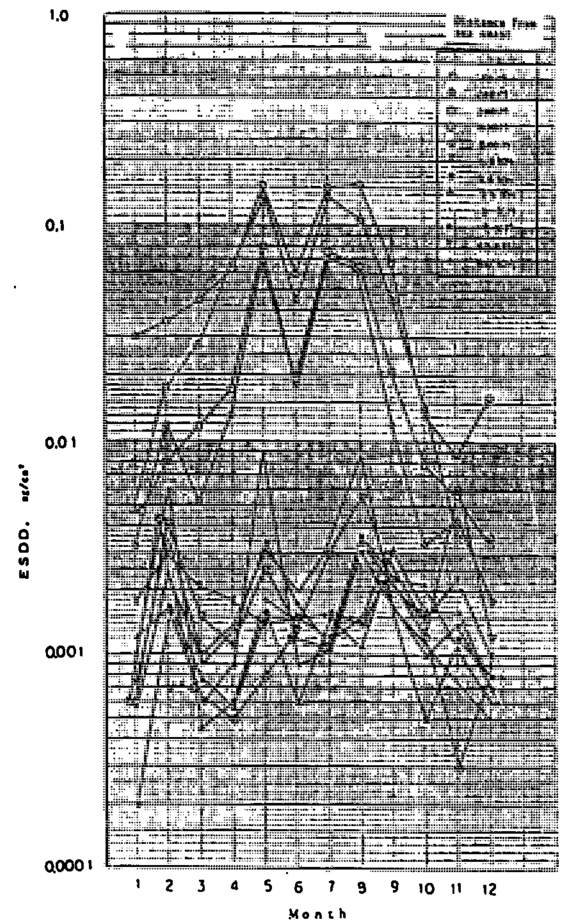

Figure 18 - Monthly variation of ESDD in Sri Lanka

The required creepage distances of the suspension discs are based on the system voltage and are selected depending on the expected level of pollution. IEC 71-3 on insulation co-ordination has given four provisional scale of natural pollution levels. These are

No significant pollution This includes areas with low density of industries or houses equipped with heating plants but subjected to frequent winds and\or rainfalls. These areas must be situated far from the sea or at high altitude.

IEC 71 - 3 also reports that no faults are observed in high humidity conditions on 145 kV lines (corresponding to 132 kV system voltage) even when equipped with less than 9 or 10 insulator units of the normal type [diameter 254 mm, spacing 146mm, creepage 300 mm]. Similarly with less than 15 units on 245 kV lines [220 kV system]. A creepage distance of 20 - 25 mm/kV_{rms} phase-to-earth is recommended for this category.

Light pollution This includes areas with industries not producing particularly polluting smoke, or areas with a high density of industries but subjected to frequent winds and/or rainfalls. These areas must be situated at least 1 km from the sea.

IEC 71 - 3 also reports that faults are observed in high humidity conditions on 145 kV lines with less than 9 or 10 insulator units of the normal type and with less than 15 units on 245 kV lines.

A creepage distance of 30 - 35 mm/kV_{rms} phase-to-earth is recommended for this category.

Heavy pollution This includes areas with a high density of industries and suburbs of large cities with high density of heating plants producing pollution. Areas close to the sea or exposed to relatively strong winds from the sea.

IEC 71 - 3 also reports that faults are observed in high humidity conditions or when wind blows from the sea unless the number of units per string is exceptionally high (more than 11 or 12 insulator units of the normal type on 145 kV lines and more than 18 units on 245 kV lines).

A creepage distance of 40 - 50 mm/kV_{rms} phase-to-earth is recommended for this category.

Very heavy pollution This includes areas of moderate extent subjected to industrial smokes producing particularly thick conductive deposits and areas of moderate extent very close to the coast and exposed to very strong and polluting winds from the sea.

IEC 71 - 3 also reports that faults are observed in high humidity conditions or salt storms even when equipped with antipollution-type insulators, unless the number of units per string is exceptionally high (more than 11 or 12 anti-pollution units on 145 kV lines and more than 18 anti-pollution units on 245 kV lines).

A creepage distance exceeding 60 mm/kV_{rms} phase-to-earth is recommended for this category.

In selecting the number of units, for lines up to 220 kV, one additional unit may be used to allow for a unit becoming defective. Also tension insulator units have their axis more or less horizontal and are more affected by rain. Also a failure of tension insulators are more severe than of suspension insulators. Thus one additional disc is used on tension insulators.

I believe, we uniformly specify 12 units for suspension units and 13 units for tension units. Are these numbers really required for all locations. Should we not evaluate and see whether a lower number of insulators can in fact be used in some locations. The cost reduction could be tremendous. The Indian practice of I believe 8-9 units for 132 KV and 14-15 units for 220 kV may be too low, but a reduction is perhaps possible for sections of lines not along the coast. In fact for those close to the sea a lower number, but of the anti-pollution type could be used.

The pollution levels on the 220 kV line should be the same as those of 132 kV lines situated in similar areas. Thus if 17 units are acceptable for 220 kV with our conditions, a reduction should definitely be possible. Further, for the 132 kV and 220 kV systems provided with proper shielding and low tower footing resistance (say less than about 7 - 10 Ω) the inherent reduction of outages helps the use of a lower number of units. The decision should be taken after considering all economic considerations including that of any unserved energy.

Pin corrosion of suspension insulator units is a serious problem resulting in a reduction of mechanical strength. Even with alternating currents, possibly due to unequal current during positive and negative half cycles, electrolytic corrosion is considered to occur and be the cause of the severe erosion. The pin must thus be protected against corrosion by attaching a sacrificial electrode to the pin at the cement boundary. The use of a pure zinc sleeve metallurgically fused to the galvanised steel pin has been shown in the field to give greatly reduced corrosion. Thus for longer life and cost effectiveness, zinc sleeve protected pin disc units must be used.

Two of the most widely used inorganic materials for the dielectric of suspension insulator units is porcelain and Toughened glass. Although both materials are silicate based ceramics, porcelain and glass are not really alike.

Porcelain insulators are made by first molding or machining the raw materials in the form of a paste, drying, glazing and finally firing in a kiln. Porcelain has porous internal structure and microcracks can appear on the surface through aging. Further, the expansion coefficient of porcelain is about 35-45% less than that of the cap, pin and cement. Thus thermal stresses can occur in addition to the electrical stresses. Porcelain insulators are vulnerable to puncture due to steep front voltage impulses due to its porosity and possible inclusions.

Toughened glass insulators are made by first melting all the raw materials in a furnace, where complete fusion into liquid glass takes place. During molding and toughening, no solid particles form in the solution, nor does crystallization occur. This results in a completely uniform vitreous structure. Permanent compressive prestresses are imparted into the surface of the glass shell by a controlled cooling process known as toughening. The expansion coefficient of toughened glass insulators do not puncture at even the steepest wavefronts occurring due to its homogeneous internal structure. For the same strength, toughened glass insulators weigh only 70% that of porcelain.

Thus there may be long term gains by specifying toughened glass insulator units only for both 132 kV and 220 kV.

Earth ing Resistance

The value of the earthing resistance plays an important part in the overvoltages that may appear on the power system. However, it must be remembered that the earthing resistance measured by the 'Megger' is not the value that will be present under actual operating conditions. This is because the value of the resistance is dependant on both the voltage and the duration. For high current impulse waveforms, the effective earthing resistance can be much lower than the measured value. Typically, a measured resistance of 120 Ω on sandy ground may come down to about 25Ω at 10 kA, whereas a resistance of 10 Ω may come down to only about 6 Ω. Tower resistances can be brought down using driven rods in and around the tower.

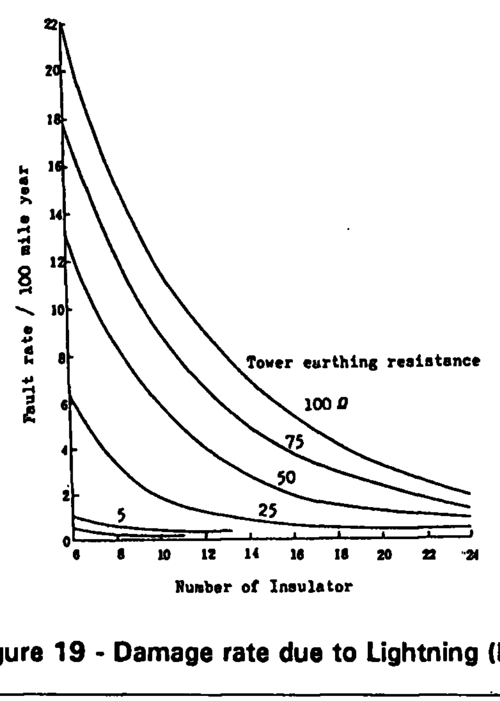

Figure 19 - Damage rate due to Lightning (Ikeda)

Values of earthing resistance in excess of about 10Ω can give rise to excessive voltages building on the tower and to back flashovers. A low tower footing resistance is essential to prevent back flashovers from the tower back to the transmission line.

Figure 19 shows how the fault rate per 100 miles in the 100-300 kV lines rapidly increases as the footing resistance increases from 5 to 100 Ω.

At the substation itself, the earthing resistance is usually kept very low, so that no back flashover would occur on the tower closest to the station. Thus dangerous overvoltages on this account due to close lightning are avoided. Towers further away along the line may have back flashover rates of the order of 0.015 per tower per year. [This would of course depend on the keraunic level in the area]. This would give about 6 back flashovers per year per 100 km long line. However, all these back flashovers would not have the same dangerous effect on the substation equipment, as those struck further away would have their surges attenuated by corona along the way. For the second and third towers away from the substation, only about a third would cause overvoltages exceeding about 120 kV. For towers further away, the fraction of overvoltages at the substation due to backflash overs decreases some more. In fact after about 1.5 km from the substation, back flash overs to the line do not cause any significant danger to the substation equipment.

The importance of this statement is that what is important for the insulation co-ordination of the substation equipment is not the lightning activity of the entire line, but the lightning activity and the line parameters close to the substation. Averages such as the average ground flash density may therefore lead to incorrect results.

The performance of the lightning arrestor would also depend on the earthing resistance. With high earthing resistances, the limiting voltage of the arrestor would be increased by the voltage drop in the line, and thus cause a higher voltage to appear across protected equipment, especially when the equipment earth and the lightning arrestor earth are different. Thus it is essential that the earthing resistances are kept low.

Acknowledgement

Before I end this talk, I must take this opportunity of thanking the audience for patiently listening to me. In particular, I wish to thank my colleagues at the University of Moratuwa, at the Ceylon Electricity Board and at the Lanka Electricity Company whose assistance has been a great help to me in preparing this talk.

References

1. Weck, K.H., "Principles and procedure of insulation co-ordination", IEE Proc, Vol 134, Part C, No 2, March 1987, pp 145-152.

2. IEEE Committee Report, "A simplified method of estimating lightning performance of transmission lines", IEEE Trans, Vol PAS - 104, No 4, April 1985, pp 919-932.

3. CEB literature

4. Diesendorf, W., "Insulation Co-ordination in high voltage electric power systems", Butterworth, London.

5. IEC Publications 71-1; 1976, 71-2: 1976, 71-3: 1982 "Insulation Co-ordination"

6. Razevig, D.V. "High Voltage Engineering", Khanna Publishers, Delhi, 1972 (Translation by M.P. Chourasia)

7. Gallagher, T.J. and Pearmain, A.J., "High Voltage Measurement, Testing and Design", John Wiley & Sons, August 1984.

8. Robinson, I., Derler, F., and Schultz, K., "Statistical evaluation of oil/transformerboard surface creepage tests for the development of barrier boards for use in power transformers", SEAMA Conf., Brighton, 1993.

9. Technical Seminar literature, NGK Insulators Ltd, February 1991, Colombo.

10. Morita, K., Imokoma, T., Suzuki, Y., "Hardware corrosion of suspension insulators on overhead transmission lines", 6th CEPSI, Jakarta, Nov 1988.

11. Westinghouse Electrical Corporation, "Electrical Transmission and Distribution Reference Book", 1964.

APPENDICES

Table 1 - Typical Lightning Arrester Characteristics

System Voltage kV rms	Rated Voltage kV rms	Maximum Continuous Operating voltage (MCOV) kV rms	Temporary Over Voltage Capability 10s (TOV) kV rms	Maximum Residual Voltage (10 kA, 8/20 μs) kV crest
36	30	24	33	83
	33	26.4	36.3	94.4
	36	28.8	39.6	96
	39	31.2	42.9	106
145	108	86	119	288
	120	92	132	320
	132	92	145	352
	138	92	152	369
	144	92	158	384
245	180	144	198	474
	192	154	211	505
	198	156	218	521
	210	156	231	553
	216	156	238	569
	228	156	251	600

Table 2 - Separation distances for Lightning Arresters

Nominal System Voltage kV	Incoming wave kV (peak)	Lightning impulse Withstand Level (LIWL) kVpeak	Arrestor Rating kV	Discharge Voltage (kV) at			Protective distance m	
				5 kA	10 kA	20 kA	1200kV/μs	2000kV/μs
145	800	650	120	300	320	356	24	10
245	1300	1050	192	473	505	561	50	25

Table 3 - Typical IEC Insulation Withstand Levels of 254 mm/146 mm standard insulator discs

No. of discs	Dry f.o.v. kV_{rms}	Wet f.o.v. kV_{rms}	Impulse f.o.v. kV_{crest}
1	75	45	110
2	130	75	195
3	180	115	275
4	235	155	360
5	280	195	430
6	325	230	505
7	375	265	580
8	420	300	660
9	465	325	730
10	510	375	800
11	550	410	880
12	595	440	955
13	635	475	1025
14	675	510	1095
16	755	570	1230
18	855	635	1370
20	915	700	1510
25	1100	855	1850
30	1290	990	2200

Table 4 - Number of insulator units (Indian Practice)

Rated System Voltage kV_{rms}	Tension Insulators		Suspension Insulators	
	Impulse f.o.v. kV	No. of discs	Impulse f.o.v. kV	No. of discs
36	320	3	320	3
145	775	9	700	8
245	1210	15	1140	14

Table 5 - Recommended Number of insulator units

System Voltage kV	Pollution Level ESDD (mg/cm^2)	Normal discs 254 mm x 146 mm	Fog type discs 254 mm x 146 mm
69	A 0.063	5	4
	B 0.125	6	4
	C 0.250	7	5
	D 0.500	7	5
138	A	10	8
	B	12	8
	C	13	9
	D	14	9
230	A	16	13
	B	19	13
	C	22	14
	D	23	15

Table 6 - Withstand Levels and minimum clearances

System Voltage kV_{rms}	Lightning Withstand Voltage kV_{peak}	Power Frequency Withstand Voltage kV_{peak}	Minimum Clearance phase-phase mm
12	60	28	90
	75	28	120
36	145	70	270
	170	70	320
145	550	230	1100
	650	275	1300
245	850	360	1700
	950	395	1900
	1050	460	2100