UPRATING OF OVERHEAD LINES

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B.E., M.Tech. (Electrical Engineering)

Thesis submitted to Cardiff University in candidature for the degree of

Doctor of Philosophy

School of Engineering

Cardiff University, Cardiff

2011

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude and thanks to my supervisors Professor A. (Manu) Haddad and Dr. Huw Griffiths for their regular guidance, encouragement and advice throughout my PhD. I would also like to thank Dr. Noureddine Harid for his advice and support.

My sincere thank goes to the "Engineering and Physical Sciences Research Council (EPSRC)" for the financial support to this project. I would also like to thank the "Higher Education Funding Council for Wales (HEFCW)" for supporting my study under Overseas Research Students Award Scheme (ORSAS).

I would like to thank National Grid, EDF Energy, E-On, SP Power System Limited, and Balfour Betty Power Networks for providing invaluable input and feedback throughout the duration of this project.

Thanks to all my friends within High Voltage Energy Systems Research Group for their friendship and continuous support through discussions. Thanks to Dr. Razib Rashedin, Dr. Maurizio Albano, Dr. Venkatesan Sreerangachetty and, Dr. Athanasios Dimopoulos for their valuable input in my research work.

My special thanks go to my parents, brother and sister for their prolonged support and encouragement. Last but not the least, I would like to thank and dedicate this thesis to my beloved wife (Sanju) and my two little boys (Bibhu and Bishesh) for their patience, continuous support and encouragement throughout the good and bad days of my research.

ABSTRACT

This thesis establishes a rigorous procedure for overhead line uprating with guidance for calculating the increase in voltage rating that may be achieved for given configurations. It initially investigates different technical issues and conventional methods of voltage uprating of overhead transmission lines. Various issues such as clearance, insulation, pollution, transient overvoltages, surge arresters; and its combinations were studied for optimised insulation coordination of voltage uprated transmission systems with reference to international standard IEC 60071 and British standard BSEN 50341. It then considers a case of existing 275kV line in 'L3' structures to analyse these issues and propose appropriate process for its possible uprating to 400kV system.

In this investigation, overhead line uprating techniques used by different utilities around the world, as published in the literature were analysed. It was found that, the decision to uprate overhead lines is influenced by technical, institutional and financial issues. In this thesis, issues such as conductor air clearance, insulation electrical strength and overvoltages are investigated and taken into account to develop an appropriate methodology. For uprating overhead lines, an exemplar case study of uprating an L3, 275kV line to 400kV was used, introducing minimum structural changes to the tower. The selection of the L3 tower is made on the basis that it is not readily upratable to 400kV due to restricted air clearances it offers.

This work has demonstrated that the voltage uprating of overhead transmission lines is possible with minimal modification to the existing line. In this case, the phase-to-earth clearance was found to be the critical factor which determines the level to which the voltage level of the line can be increased. Computations of overvoltages due to switching and lightning phenomena were conducted to estimate overvoltage levels and optimise the protection scheme required to minimise the required minimum electrical clearances. Employing gapless metal-oxide line surge arresters were proposed to be the most effective solution to control the overvoltages, thereby reducing the minimum phase-to-earth clearance requirements. This solution is preferred to modifying the tower structure in order to achieve the required clearance for 400kV system. The study of lightning and switching surge performances along the line under different arrester configurations was carried out so that the appropriate surge arrester configuration could be selected to maintain overvoltage levels within the targeted withstand level for the line. The extensive transient simulations performed in this work identified that, for a double circuit overhead transmission line as used on the UK system, the top-most phase conductors are prone to shielding failure lightning strikes whilst the bottom-most phase conductors are likely to be subjected to backflashover surges for the case of high tower footing resistance.

The assessment of electric and magnetic field profiles of a 275kV line uprated to 400kV was computed. It showed that, the field intensities of voltage uprated lines are within the limits adopted by national and international standards and requires no additional wayleave for uprating.

LIST OF PUBLICATIONS

1. **R. Bhattarai**, A. Haddad, H. Griffiths, and N. Harid, "Voltage Uprating of Overhead Transmission Lines," in *45th International University Power Engineering Conference (UPEC)*, Cardiff, UK, Aug.-Sep. 2010.

2. **R. Bhattarai**, H. Griffiths, N. Harid, and A. Haddad, "Calculation of Energy Stress on Surge Arresters in 275kV Transmission Lines," in *16th International Symposium on High Voltage Engineering (ISH)*, Cape Town, South Africa, Aug. 2009.

3. **R. Bhattarai**, N. Harid, H. Griffiths, and A. Haddad, "Application of Surge Arresters for Lightning Protection of 33kV Wood Pole Distribution Lines," in *20th International Conference and Exhibition on Electricity Distribution (CIRED)*, Prague, Czech Republic, Jun. 2009.

4. **R. Bhattarai**, R. Rashedin, S. Venkatesan, A. Haddad, H. Griffiths, and N. Harid, "Lightning Performance of 275kV Transmission Lines," in *43rd International University Power Engineering Conference (UPEC)*, Padova, Italy, Sep. 2008.

5. S. Venkatesan, **R. Bhattarai**, M. Osborne, A. Haddad, H. Griffiths, and N. Harid, "A Case Study on Voltage Uprating of Overhead Lines – Air Clearance Requirements," in *45th International University Power Engineering Conference (UPEC)*, Cardiff, UK, Aug.-Sep. 2010.

6. S. Venkatesan, R. Rasheddin, **R. Bhattarai**, A. Haddad, N. Harid, and H. Griffiths, "Significance of Switching Impulse Breakdown Voltage Characteristics in voltage Uprating," in *XVII International Conference on Gas Discharge and their Application (GD)*, Cardiff, UK, Sep. 2008.

GLOSSARY OF TERMS

AAAC	All Aluminium Alloy Conductor
ACSR	Aluminium Conductor Steel Reinforced
ATP	Alternative Transients Program
BFR	Backflashover Rate
BS	British Standard
BSEN	British Standard European Norm
CEU	Council of the European Union
CFO	Critical Flashover Voltage
CIGRE	International Council on Large Electric Systems
CRIEPI	Central Research Institute of Electric Power Industry
DE	Disruptive Effect
EGM	Electrogeometric Model
EHV	Extra High Voltage
EIA	Energy Information Administration
EMF	Electromagnetic Field
EMTP	Electromagnetic Transients Program
ENA	Energy Network Association
EPRI	Electric Power Research Institute
EPSRC	Engineering and Physical Sciences Research Council
EXB	Expanded Bundle
GFD	Ground Flash Density
GPS	Geographic Positioning System
HSIL	High Surge Impedance Loading
HTLS	High Temperature Low Sag

HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
MCOV	Maximum Continuous Operating Voltage
NESC	National Electrical Safety Code
NG	National Grid
NNA	National Normative Aspects
NRPB	National Radiological Protection Board
Ofgem	Office of the Gas and Electricity Market
(R) USCD	(Reference) Unified Specific Creepage Distance
SAGE	Stakeholder Advisory Group on Extremely Low Frequency Electric and Magnetic Field
SFFR	Shielding Failure Flashover Rate
SIL	Surge Impedance Loading
SPS	Site Pollution Severity
UK	United Kingdom
USA	United States of America
WoC	Width of Corridor

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CHAPTER 1

INTRODUCTION

The development in technology and increase in the quality of life, which the most industrialised and developed countries in the world have experienced in recent decades, have led to an increasing demand for electrical power. According to the Energy Information Administration (EIA), U.S. Department of Energy [1.1], the projected growth of world net electricity generation over the next 20 years will be 2.4% per year. The statistics presented in EIA and International Energy Agency (IEA) reports [1.1, 1.2] show that the growth rate for electricity generation varies from 1% to 3% per annum in the developed countries to 4% to 17% per annum in the developing countries.

In the case of developed countries, the electrical power transmission and distribution infrastructures are 50 to 60 years old. The design life of most of the infrastructure being 50 years, they are now matured beyond their engineering performance and economic life [1.3]. With the increase in generation capacity of the system to meet increasing demand and the growth of transmission capacity often limited due to physical or environmental constraints, there is a need to transmit greater quantities of bulk electrical power through the existing transmission structure. Furthermore, due to greater unevenness in generation, distribution, e.g. off-shore wind, existing transmission systems are being progressively more congested.

In the United Kingdom (UK), the transmission system operated by National Grid comprises approximately 15,000 circuit kilometres of 275kV and 400kV overhead lines supported by more than 26,000 transmission towers [1.4, 1.5]. This network of power lines was constructed mainly during the 1950s and 1960s, and much of the system is almost at the end of its anticipated technical life [1.6, 1.7]. According to National Grid, the peak unrestricted demand on the national electricity transmission system in 'average cold spell' conditions will rise from 57.6GW in 2009/10 to 62.8GW by 2016/17 with an average growth rate of 1.2% per annum [1.8]. On the other hand, to meet the British Government's 2020 target on climate change and renewable energy, a major change in generation capacity is required that may add an additional 32GW generation from wind and 17GW from new non-renewable generation, and this will be required to be transmitted through the grid [1.8, 1.9]. Such changes mean the size and location of generation connected to the grid will change considerably. The advancement in technology with the possible introduction of demand management could also lead the electricity demand pattern to change. To accommodate these changes in generation and demand, there will be a need for an electricity grid with larger capacity and the ability to manage greater fluctuations in electricity demand and supply. However, the majority of the lines in the existing 50-60 years old network in UK are running at their full capacity and therefore, may not be able to manage future scenarios. In general, the major power flow on the UK transmission system is from North to South. The lines between Scotland and England are operating at their full capacity and also a numbers of 275kV lines within the Scottish Power Transmission network are highly strained [1.9]. Other circuits within the UK network are overloaded due to increasing clustering of generators in particular areas. For example, significant generation development is proposed in East Anglia that is expected to connect 8.4GW between 2011 and 2021 [1.10]. Additional 5GW from wind farms (2014-2020) may also connect to the existing system in East Anglia. The transmission circuits in this part of the grid are already running close to their full capacity and changes will be required to accommodate this new generation [1.10]. Figure 1.1 shows the expected change in power flow pattern in the UK power network between 2010/11 and 2016/17 [1.8]. As can be seen in the figure, the line

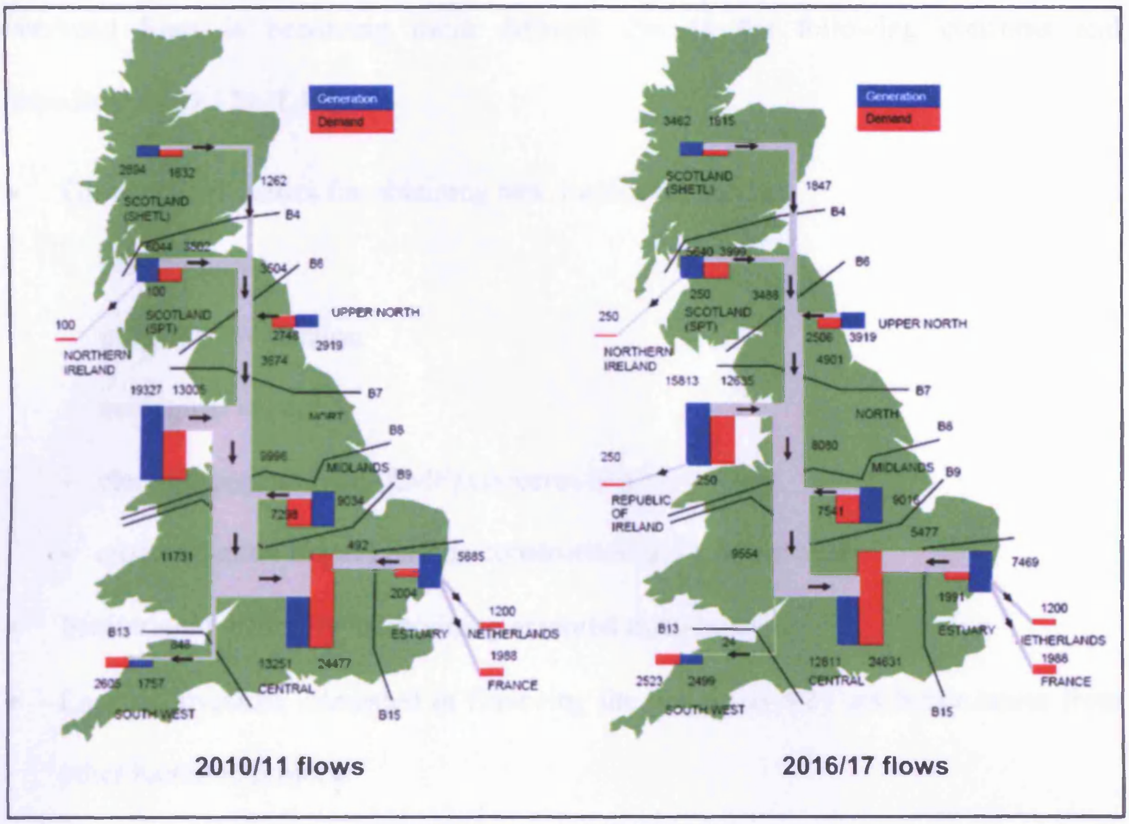


Figure 1.1: Changes in power flow pattern in the United Kingdom [1.8].

between north and south Scotland and between south-east (estuary) to central England is predicted to increase its loading.

The solution to this marked increase in predicted power flow is to either to construct new lines or to increase transmission capacity by uprating or upgrading the existing line. In the UK, there are on-going projects to construct new lines (e.g. Beauly-Denny 400kV system [1.9]) in Scotland. In addition, the main Scotland - England interconnections are proposed to be uprated (e.g. Overhead line between Stella West and Eccles, Stella West and Spennymoor [1.11]) and some lines to upgrade (e.g. Dounreay-Beauly-Kintore 275kV upgrade [1.9]).

In a global context, with the increase in population and urban expansion, the construction of new transmission grid is limited to a certain extent. Constructing new overhead lines is becoming more difficult due to the following concerns and impediments [1.12 – 1.14]:

- Growing difficulties for obtaining new wayleaves due to
  - visual impact
  - property devaluation
  - ecological impact
  - electromagnetic field (EMF) concerns to public health
  - environmental impact on line construction and maintenance
- Institutional difficulty in obtaining essential authorisation
- Lack of investors interested in financing the project as they get better return from other lucrative projects

In the future, utilities are expecting growing pressures from regulators and are looking for different ways to minimise their costs. The opportunity to increase the transmission capacity by uprating existing lines is therefore of interest because it can be done at significantly less cost than building a new overhead line and with a shorter lead-time.

1.1 Aims and Objectives

The aims and objectives of this thesis are to find uprating solutions to increase the capacity of existing overhead lines. To achieve this, three different approaches are available.

- Increase current carrying capacity of line conductors
- Convert line operation from AC into HVDC
- Increase voltage rating of the line

Previously, much research was carried out to find technical and economical solutions to increased transmission capacity requirements. Many utilities around the world have increased the capacity of overhead lines by improving current carrying capacity [1.15 – 1.20]. In the United Kingdom, National Grid (NG) has increased the current carrying capacity of lines through the installation of high temperature low sag conductor [1.21]. However, to increase the current carrying capacity of lines, the majority of the techniques require the structural modification of the line or change in existing conductor with high temperature low sag conductor [1.22] together with longer outage problem.

On the other hand, even though the conversion of a long AC transmission line to HVDC is economical and technically feasible and can offer benefits in terms of system stability and control, the overall cost for a HVDC line up to certain distance (breakeven distance) is high due to the high cost of terminal equipments used in converter stations [1.23, 1.24]. Therefore, this method is not economically suitable for short and medium lines.

While current uprating and HVDC solutions are being adopted, there has been less attention given to voltage uprating. The major challenge in this approach is the need to raise and/or modify transmission line structures/supports in order to comply with the minimum safety distances. With voltage uprating, the challenge to increase the insulation strength of the line requires better insulation coordination techniques. At the same time, lightning and switching overvoltages require additional air clearances in the system. Therefore, it is required to have new, improved insulation coordination techniques as well as the optimal application of overvoltage protective devices to ensure safe operation of the uprated line, thereby minimising structural modification of the existing line. Accordingly, the two main objectives of this research are;

- To quantify the effect on overvoltage levels and protection margins of various system parameters such as clearance, insulation, pollution, transient overvoltages, surge arresters; and their combinations for optimised insulation coordination of voltage-uprated overhead transmission systems.

- To establish a rigorous procedure for future overhead line uprating projects with guidance for calculating the increase in voltage rating that may be achieved from various measures.

1.2 Contribution of Present Work

The important contributions achieved during the course of this research work are as follows.

- Extensive critical review of different uprating methods and associated techniques researched and/or implemented including cases of uprated lines in different countries.
- Optimised insulation coordination process for transient and temporary overvoltages for determination of risk of failure following voltage uprating of overhead transmission systems.
- Novel analysis of electrical clearance issues and insulation electrical strength of an existing line to establish apposite technique for overhead line uprating.
- Computation of overvoltages due to switching and lightning phenomena to estimate overvoltage level and optimisation of the protection scheme required to minimise the required minimum electrical clearances.
- Recommendations of cost effective appropriate surge arrester configuration for effective control of lightning overvoltage within the targeted withstand level.
- Assessment of electric and magnetic fields in voltage-uprated line to ensure public safety and to identify requirements for additional wayleave.

1.3 Thesis Content

An extensive review of different methods and techniques investigated and practiced by researchers and utilities around the world are presented in Chapter 2. The review covers different options of increasing utilisation and differentiates uprating from other available options such as upgrading, refurbishment, life extension, and expansion. This chapter also presents an overview of developments in overhead line uprating together with a listing of uprating projects around the world.

In Chapter 3, the insulation coordination process required for voltage uprating is theoretically analysed. The coordination process is explained for both transient and temporary overvoltages to identify clearance requirements for the standard insulation level under different overvoltages. Insulation levels are also assessed based on different pollution levels.

Chapter 4 deals with the determination of the available electrical clearances in the case of an existing 275kV overhead transmission line, and compares the values with required electrical clearances for uprating to a 400kV system. The requirements for additional insulation and conductor air clearances for voltage uprating are identified.

To provide additional clearances for an uprated voltage level, the option of modification of an existing structure is replaced by the alternative approach of reducing the overvoltage level in the system so that the required minimum clearance distance for uprated voltage level itself is reduced. In order to explore this possibility, computation of switching and lightning overvoltages is included in Chapter 5. In this chapter, application of an appropriate line surge arrester configuration for an effective switching overvoltage control is also shown.

In Chapter 6, the appropriate surge arrester configuration for the control of lightning overvoltage under shielding failure and backflash is covered. The effect of tower footing resistance on overvoltage which can directly influence the proposed alternative concept of voltage uprating by reducing required minimum clearance distance is discussed in the chapter. Lightning performance analysis of a 275kV transmission line uprated to 400kV is performed together with arrester energy duty and its risk of failure.

In Chapter 7, in order to identify any potential environmental and public health effect, electric and magnetic fields are computed for proposed uprated line. The values are compared with those produced prior to uprating and also another conventional line of the same voltage level. The field profiles for the uprated line are checked against the limits of electric and magnetic field exposure in the UK.

CHAPTER 2

UPRATING OF OVERHEAD LINES: A REVIEW

The term *uprating* is derived from the word *rating* (noun) which in the English language appears as a classification or ranking based on quality, standard, or performance [2.1]. In the general context of electrical terms, *rating* means the load which a machine or apparatus is designed to carry under specified conditions, which varies according to the kind of rating in question [2.2]. In the context of this specific work, the *rating* is the apparent power capacity of the line. Therefore, the term *uprating* should be understood as increasing the power capacity of the line.

2.1 INTRODUCTION

In recent years, increasing power transfer capability of overhead lines has become of interest to electric utilities all over the world to deal with increasing demand for power. There are various techniques used around the world to increase the power transfer capability of overhead lines. Power being multiple of current and voltage, all these adopted techniques either result in increasing the overhead line current capability, voltage capability, or both. The selection of an appropriate technique for uprating a particular overhead line is not an easy task. It depends upon the future requirement of the line capacity, the existing line parameters together with line design and construction methods. Consideration must be given not only to electrical limitations but also to physical limitations, operator constraints and economics.

An ultimate purpose of this thesis is to contribute towards development of a comprehensive and innovative procedure for voltage uprating of overhead transmission lines that helps increase utilisation of existing systems with careful consideration of the costs. Initially, however, it is essential to scrutinise other different available techniques for increasing utilisation of existing transmission systems. Therefore, the first part of this chapter reviews different options for increasing utilisation and differentiates uprating from other available options.

Next, the various constraints on the power transfer capability of overhead lines and requirements for overhead line uprating are considered. Thermal, voltage and operation related constraints are discussed in detail. Different factors that influence the decision making for uprating existing lines as opposed to building a new line are considered.

In the following section, different uprating methods investigated and practised by researchers and utilities around the world are extensively reviewed. Both current and voltage uprating techniques are discussed together with examples of application of such techniques in several cases of uprating in different countries. Environmental effects of overhead line uprating are also discussed. Finally, a brief history of overhead line uprating is presented including a list of uprating works around the world.

2.2 Overhead Line Increased Utilisation Options

Uprating is one option for increasing utilisation of existing assets. In the context of overhead lines, there are several options for increasing utilisation. CIGRE Technical Brochure 353 [2.3] gives options for increasing utilisation of overhead transmission line as shown in Figure 2.1. This brochure also provides guidelines for economic and technical considerations for transmission line asset renewal and any combination of uprating, upgrading, refurbishment and asset expansion.

The choice of the appropriate method to increase the utilisation of existing overhead lines is influenced by different factors. The limitation of the existing overhead line and its future needs are the two key issues to be addressed. If the limitation is due to voltage control, stability or maximum power flow, then uprating could be the best choice. However, upgrading is done to improve the reliability of the existing line and refurbishment is done to restore or extend the working life of the line. Table 2.1 gives a general overview of each option, and clearly differentiates uprating from the other options of increasing utilisation [2.3].

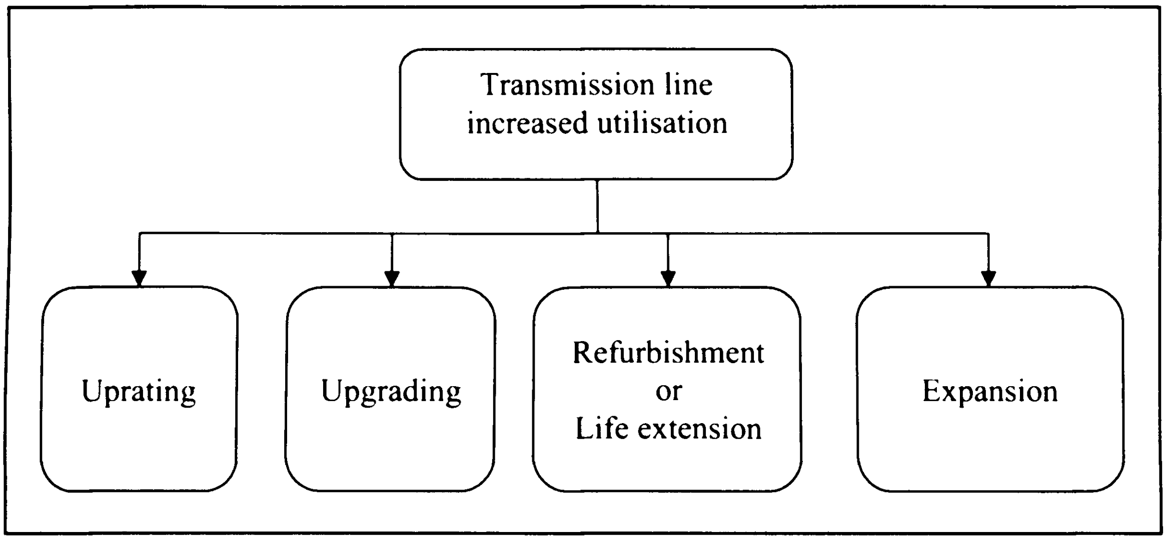


Figure 2.1: Transmission line increased utilisation options [2.3].

Table 2.1: Overview of transmission line increased utilisation options [2.3]. Symbols shown are represented as: increased (↑), decreased (↓), unchanged (=).

Terminology	Definition	Failure probability, P	Failure consequence, C	Failure risk, (R = P × C)	Driver	Action	Proposition
Uprating	Increasing capacity	–	↑	↑	increase thermal rating by	installing	higher capacity conductors additional conductors active line rating systems
						increasing	conductor tension conductor attachment height
						adopting	probabilistic ratings
						redesign	high surge impedance performance
					increase voltage rating by	increasing	insulation electrical strength conductor attachment height
Upgrading	Improving reliability	↓	–	↓	improve structural performance by	increasing	structure strength foundation strength
					improve electrical performance by	improving	insulation pollution performance lightning performance by improving insulation lightning performance by improving earthing lightning performance by installing earth wires
						reducing	structure potential rise electrical induction
						installing	lightning arresters

Refurbishment	Restoring to design working life	↓ – ↓	arrest degradation by	restoring	structure strength foundation strength conductor strength and capacity insulation pollution performance fitting strength lightning performance
Life Extension	Repairing without restoring to original design life	↓ = ↓	arrest degradation by	repairing	structures foundations conductors insulators fittings earthing earth wires
Expansion		↓ – ↓	improve availability by	increasing	maintainability by adopting live line techniques
		– ↑ ↑	provide third party access by	installing	telecommunication equipment fibre optic

2.2.1 Review of Definitions

In reviewing certain published literature [2.4 – 2.7], it has been found that it is difficult to differentiate between the options for increasing utilisation of overhead lines. For example, similar meanings are provided for uprating and upgrading. In many cases [2.7], life extension, refurbishment, and expansions are considered all within uprating or upgrading processes. The Electric Power Research Institute (EPRI)'s transmission line uprating guide [2.8] defines uprating as "Increase in the power transmission capacity of overhead lines". In CIGRE Technical Brochure No. 175 [2.9] uprating is defined as "Improving electrical characteristics of an overhead line" and upgrading is defined as "Strengthening line components". However, CIGRE Technical Brochure No. 294 [2.10] provides the following definition of uprating and upgrading.

- Uprating of a line is the increase in its transmission capacity
- Upgrading of a line means improvement of its structural reliability

This document also differentiates refurbishment from life extension and expansion. A more recently published CIGRE Technical Brochure No. 353 [2.3] provides the most comprehensive definitions and classification of all options for increasing utilisation of overhead lines.

2.2.2 CIGRE Definitions

CIGRE Technical Brochure No. 353 [2.3] provides the following definitions for different options used in increasing utilisation of overhead lines.

- ***Uprating:*** Increasing the electrical characteristics of a line due to, for example, a requirement for higher electrical capacity or large clearances. Uprating will increase the electrical capacity of the line thereby potentially increasing the consequences of a failure.
- ***Upgrading:*** Increasing the original mechanical strength of an item due to, for example, a requirement for higher meteorological actions. Upgrading does not change the consequences of failure but decrease probability of failure.
- ***Refurbishment:*** Extensive renovation or repair of an item to restore their intended design working life. Refurbishment results in a decrease of the probability of failure and no change to the consequence of failure.
- ***Life Extension:*** Extensive renovation or repair of an item without restoring their original design working life. If the original design working life is restored, life extension becomes refurbishment. Life extension results in a decrease of the probability of failure and no change to the consequence of failure.
- ***Expansion:*** Increasing the functionality of transmission line components.

Therefore, uprating of overhead lines means increasing its MVA capacity without any wholesale structural modifications, reconstruction, or replacement of existing structures.

2.3 Constraints of Overhead Line Uprating

Power being multiple of current and voltage, power transfer capability of overhead line is limited either by constraints related to current (thermal) or the constraints related to voltage.

2.3.1 Thermal Constraints

Thermal constraints are related to the current flowing in the line and environmental conditions. The magnitude of current continually flowing over time dissipates heat. In the case of distribution lines, and short and medium transmission lines, excessive current will overheat the line conductors resulting in thermal expansion that produce aluminium annealing and excessive sag. The consequence of increase in sag is that the minimum ground clearance for line conductor may be violated. Therefore, the power transfer capability of a line is limited by its thermal limit which is related to the current carrying capacity (current rating) of the line. According to EPRI Guide [2.8], although the thermal limit is not a function of transmission line length, the power transfer capability of lines that are shorter than 50 miles in length are more affected by its thermal limit as beyond this length transient stability restrict power transfer. Longer lines with high transfer reactance are prone to instability. For short lines, where line reactance is small, the maximum permissible power transfer to satisfy transient stability requirements could exceed the line's current carrying capacity (thermal limit). Conversely, for long lines, the stability limit may be reached before the thermal limit of the line.

Figure 2.2 shows the loading capability of a typical high voltage transmission line considering both system stability and thermal limits [2.8, 2.11]. The figure shows the amount of power transmitted for 45^0 phase shift between sending and receiving end voltage (δ) for a typical transmission line in per unit (p.u) of Surge Impedance Loading (SIL). It is clear from the figure that for short transmission lines, the thermal limit applies whereas above a certain length, the stability limit restricts. EPRI Guide [2.8] defines SIL as a product of the termination bus voltages divided by the characteristic impedance of the line. SIL is MW loading of a transmission line at which natural reactive power balance occurs between the capacitive and inductive elements of the line [2.12].

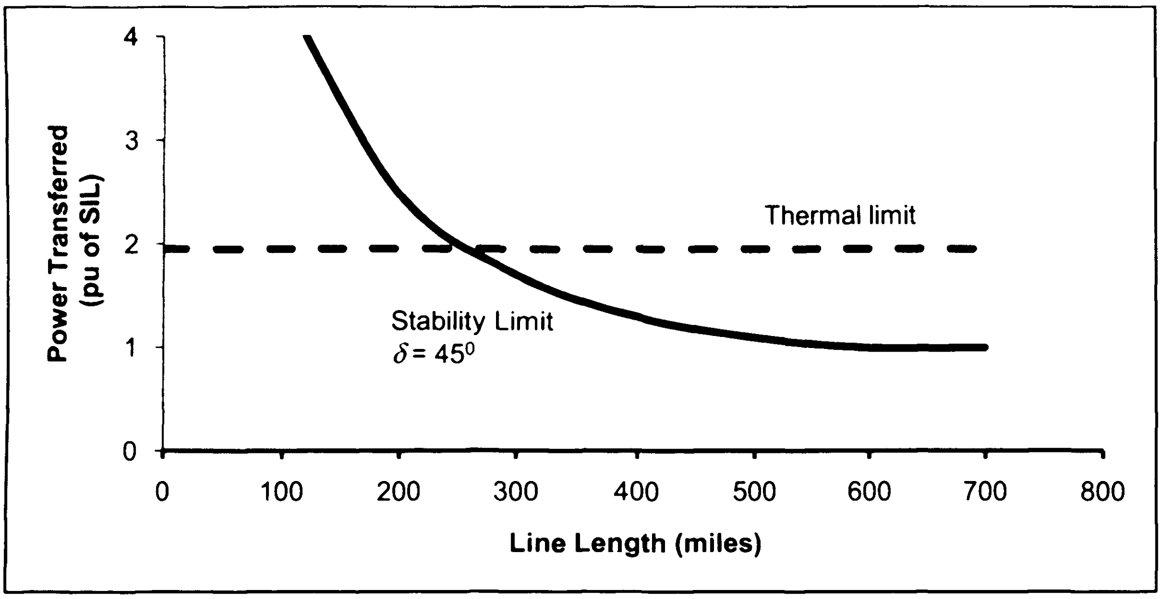


Figure 2.2: Maximum power flow considering system stability [2.8, 2.11].

2.3.2 Voltage constraints

The power transfer capacity of overhead lines is also limited by constraints related to voltage. The power transfer limit is fixed by the maximum operating nominal system voltage with some variations. Normally, the allowable variation in transmission system voltage is limited to ±5% of nominal system voltage. The upper limit of system voltage depends upon different line parameters. Overvoltage in the system can cause short circuits, radio interference and corona, while undervoltage can cause inadequate operation of equipments on the consumer's side [2.13]. To summarise, the voltage related constraints for overhead line power transfer capability are governed by [2.14]:

- Overvoltages in the system (lightning, switching and power frequency)
- Electrical clearances
- Insulation levels
- Structure designs

- Corona and noise
- Electromagnetic interference

The impulse withstand level of a system is different for each voltage class. An increase in the voltage class will result in an increased required withstand level of the system and accordingly all other design parameters will vary. The International Electrotechnical Commission (IEC) standard on Insulation Coordination (IEC-60071-1) [2.15] details the withstand levels for system voltages between 1kV and 800kV and minimum clearance requirements for electrical safety. Energy Network Association (ENA) Technical Specification 43-8 [2.16] also gives clearances required for overhead lines including ground clearance requirements. British Standard (BSEN 50341) [2.17, 2.18] applies for new overhead lines operating at 45kV and above. An increase in overvoltage withstand level increases the minimum required clearances [2.16, 2.19] resulting in modification to other system parameters such as insulation levels and structural designs. An increase in operating voltage will result in increased risk of corona that produces audible noise. The electromagnetic fields resulting from corona discharge may create radio frequency noise causing possible interference with radio frequency communication systems. For transmission lines above 500kV, audible noise must be considered in the design [2.20].

2.4 Requirements for Overhead Line Uprating

Utility operators frequently are faced with decisions of whether to upgrade or uprate transmission lines for improving power transfer capability or reliability. The decision is guided by technical, financial and environmental issues together with the characteristics of the existing system. For example, in the United Kingdom and other European countries, additional transmission capacity is now required to deal with the anticipated growth in renewable energy generations [2.21, 2.22]. Detailed system design studies of these future planned networks enable study of line performance, transmission capability, voltage drop, fault, line loss etc. The outcome of such studies can help predict the requirements for future overhead lines and accordingly facilitate planning the system.

2.4.1 Decision Making Process

The EPRI Guide on Transmission Line Uprating [2.8] sets out the decision making process on increasing capacity of overhead lines. The process is based on a question: "whether to build new lines or to develop a facility of getting an additional capacity from existing line". The choice between these two options is based on the following important factors [2.8]:

- Cause of present limitations
  - maximum power flow
  - voltage control
  - stability
  - reliability of service
- Requirement for base load or peak load
- Requirement for seasonal load or annual load
- Limitation in small area or large area of the network
- System requirements of the line and operator's policy
- Possibility of line outage
- Physical (line design and construction) and institutional considerations
- Financial characteristics and economic factors

The power flow limitation due to system stability and voltage control can be improved by reducing the per unit impedance of the line or by increasing voltage. Short-term loading contingency can be tackled by detailed analysis of the thermal rating of the line, real time monitoring and, dynamic line rating [2.8]. Power flow limitation due to reliability of the service can be addressed by improving the lightning / switching performance in combination with improved galloping and vibration performance [2.23]. In general, major lines in a network cannot be taken out of service for long periods of time. Therefore, the decision of uprating such lines is also influenced by line outage limitations. In such case, the methods that require long outage can be postponed and other short-term measures can be taken into account. For example, if the line is to be uprated by means of probabilistic and dynamic uprating methods in combination of re-conductoring, then the first two methods can be used as a temporary method before re-conductoring is done. In some cases, at distribution level where conductor clearance is not an issue, voltage uprating can be achieved by replacing insulators under live line conditions.

Further, the decision of uprating overhead lines is also strongly affected by the institutional and physical constraints. Obtaining wayleaves for the construction of a new line may be difficult, and this can be an incentive to improve capacity of existing lines [2.23]. Sometimes, government strategy and regulatory bodies (e.g. '*Ofgem*' in UK) can play significant role in the decision making process. Physical constraints are linked to the structural performance capabilities of an existing line. Constraints such as the mechanical strength of existing support structures, foundations, conductor positions in the structure, available conductor air clearance, conductor size, and insulation electrical strength are important.

In some cases, financial and economic factors are dominant. Cost includes additional wayleave, materials, construction, maintenance and operation of the uprated line [2.13, 2.23]. Before making any decision, the overall cost of line uprating is normally compared with the cost of other methods of increased utilisation and/or new construction. *Baldick and O'Neill* [2.24], *Shankle* [2.14], and *Piernot and Leahy* [2.25] compare the cost of number of conventional and emerging transmission line uprating techniques with the cost of building a new line, and based on the technical and economic factors, they recommend uprating existing lines rather than building new lines to increase power flow capacity. Sometimes, alternative and technically feasible options are available for uprating, e.g. different conductor types for reconductoring may offer different uprating capacities at different costs. In such cases, the economics of the project may dictate the conductor selection.

2.5 METHODS FOR UPRATING OVERHEAD LINES

There are numerous methods and techniques that have been applied to uprate overhead lines. The selection of the most suitable method for line uprating may vary from case to case, and will depend upon the location, characteristics and performance of the existing line. By definition, uprating an overhead line involves increasing its power transfer capability which requires either increasing its:

- current rating (Current Uprating) and / or
- voltage level (Voltage Uprating)

Examples of current uprating of lines in Ireland, UK, South Africa, and Israel are given in [2.22, 2.26 – 2.28] while projects involving voltage uprating in South Africa, USA, and Japan are described in [2.5, 2.29, 2.30]. A number of publications describe methods and techniques for current uprating [2.4, 2.13, 2.31 – 2.33] and voltage uprating [2.13, 2.33]. CIGRE Working Group B2.06, in Technical Brochure 294 [2.10], has summarised the main methods and tools to uprate overhead lines, and further details on uprating have been published by Working Group B2.13 in Technical Brochure 353 [2.3]. Based on these publications, Table 2.2 lists the most common current and voltage uprating methods together with the associated techniques and processes [2.3, 2.4, 2.10, 2.13, 2.33, 2.34].

Table 2.2: Methods for overhead line uprating [2.3, 2.4, 2.10, 2.13, 2.33, 2.34].

Uprating	Method	Technique	Process
Increasing current rate (Current Uprating)	Re-conductoring Method	Conductor replacement	Increased conductivity area
			High temperature conductors
			Composite conductor systems
		Modify rating criteria	Metrological study
	Deterministic Method	Increase conductor tension	Increase tension
			Negative sag device
		Increase conductor attachment height	Structure body extension
			Insulator crossarm
			Interspaced structures
	Probabilistic Method	Account for actual load profile	Temporary increase in rating
		Modify rating criteria	Probability based metrological study
	Real-time monitoring Method	Line thermal, sag, tension and/or climatic conditions measurement	Line sag or tension monitor
			Conductor distributed temperature sensing
			Weather station
	High surge impedance loading Method	Conductor bundling and geometry	Physical configuration
Increasing voltage level (Voltage Uprating)	Conductor air clearance	Increasing conductor attachment height	Re-tensioning
			Sag adjustment
			Increasing conductor height at attachment point
			Extension of structure height
			Terrain countering
		Increasing phase-to-phase clearance	Re-tensioning
			Line compaction
			Inter-phase spacer
			Double-circuit line to high voltage single-circuit line
	Insulation electrical strength	Re-insulation	Adding / substituting insulators
			Use of polymeric insulator
			Cross-arm modification

2.5.1 Current Uprating

Current uprating is the most common option for overhead line uprating. It is effective for short transmission lines where the line loading is limited by the thermal capacity of the conductors. An increase in current rating means an increase in conductor temperature and, hence, the method is also known as "*Ampacity Uprating*" or "*Thermal Uprating*". As defined in [2.35], "*The ampacity of a conductor is that maximum constant current which will meet the design, security and safety criteria of a particular line on which the conductor is used*" and "*Thermal Rating*" is "*The maximum electrical current, which can be safely carried in an overhead transmission line (same meaning as ampacity)*".

Different methods to achieve current uprating are explained in the following sub-sections.

2.5.1.1 Re-conductoring Method

Re-conductoring is the most common and effective method of current uprating that requires minimal modifications of existing structure. Although this method is comparatively expensive than any other current uprating method, it is cheaper than building a new line [2.24, 2.26]. Replacement by a conductor with a slightly high cross sectional area (same conductor weight) or by High Temperature Low Sag (HTLS) conductors can provide significant current uprating without any structural modification. For example, the replacement of Aluminium Conductor Steel Reinforced (ACSR) by All Aluminium Alloy Conductor (AAAC) of same cross-sectional area can improve the thermal rating up to 40% [2.35]. In the UK, AAAC is extensively used to replace ACSR which allows an increase in maximum operating temperature from 50 °C to 75 °C, with a corresponding 25% increase in thermal rating [2.32, 2.36].

Some commercially available HTLS conductors are shown in Figure 2.3 [2.35]. The

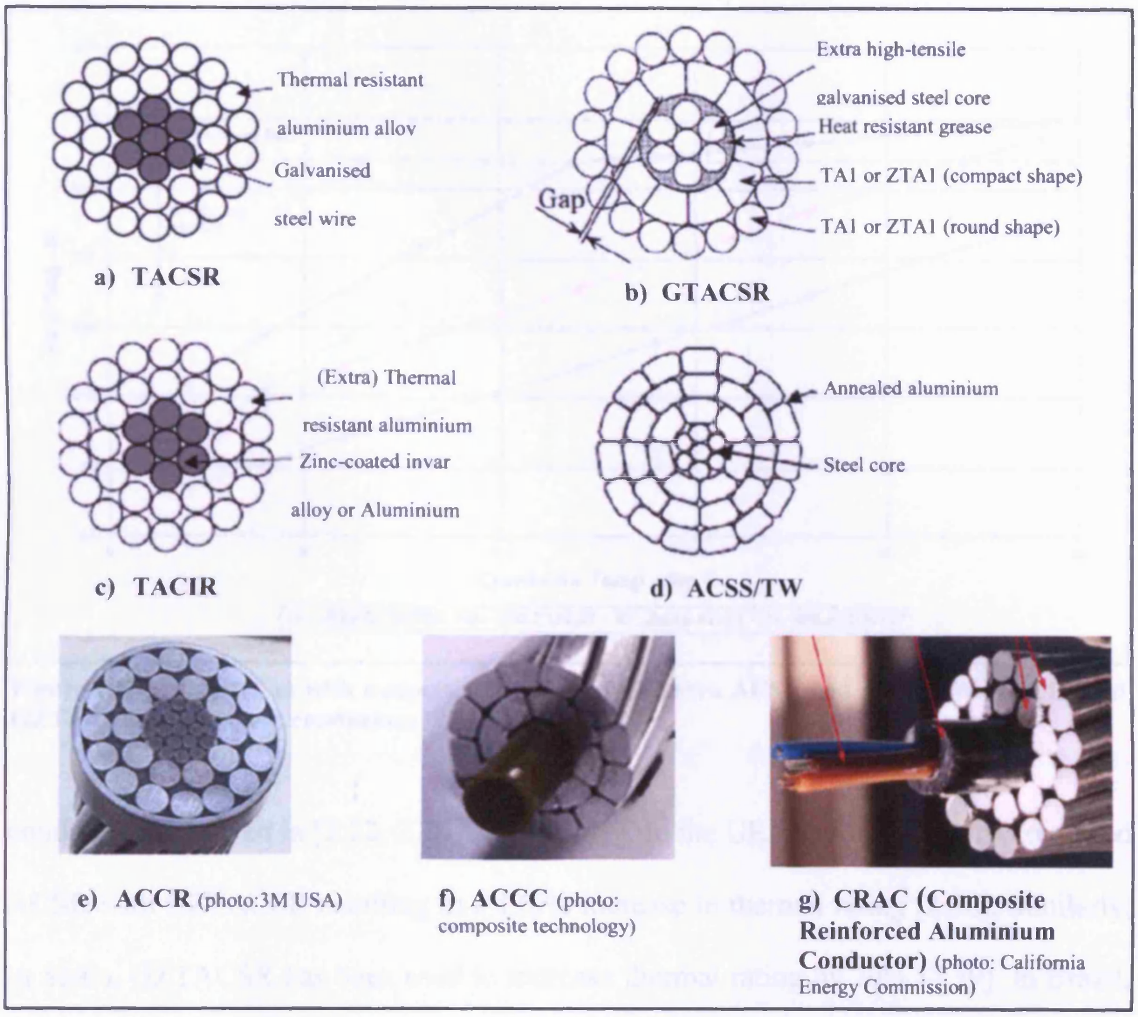


Figure 2.3: Commercially available HTLS conductors [2.35].

HTLS conductor has comparatively low sag to conductor temperature ratio i.e. the rate of increase of sag with increase in conductor temperature is low. Therefore, for the same sag, these conductors can operate at higher temperatures (above 100°C) thereby increasing the thermal rating of the overhead lines. Low sag at high temperature helps maintain required clearances without any structural modification. Figure 2.4 shows the final sag and conductor temperature relationship for different HTLS conductors based on a case study [2.35]. From the figure, it can be seen that GZTACSR has the lowest sag. According to a 2002 CIGRE report [2.37], around 20,000km of HTLS conductors had been installed around the world at that time. Examples of line uprating using HTLS

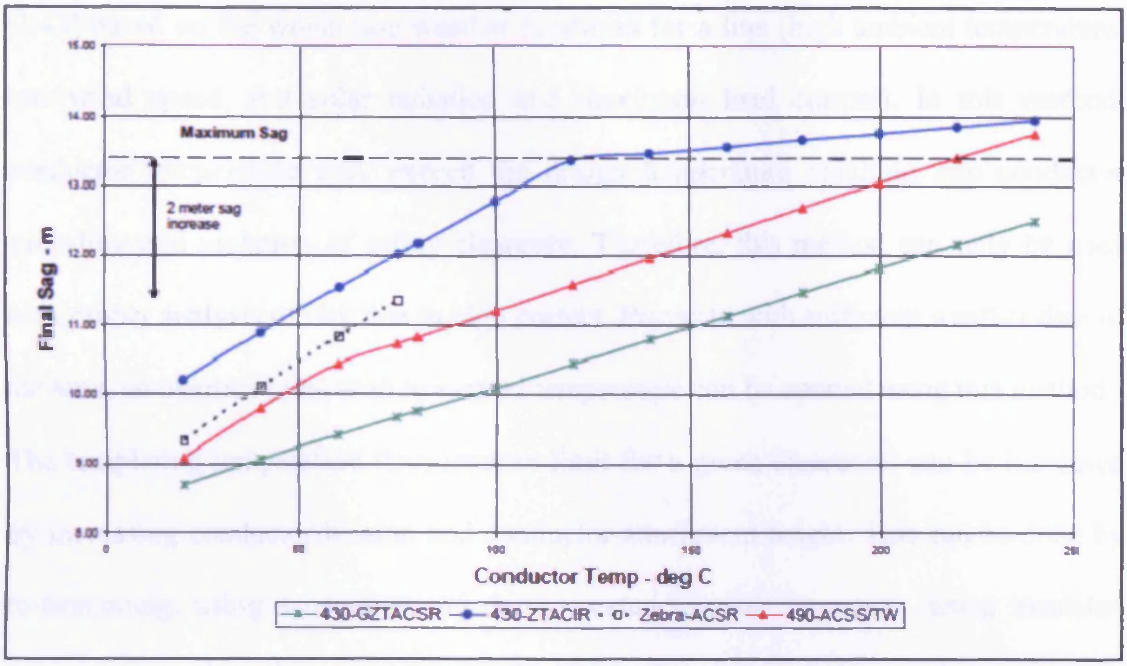


Figure 2.4: Sag variation with temperature for original Zebra ACSR and ACSS/TW, TACIR and GZTACSR replacement conductors [2.35.]

conductors are given in [2.22, 2.26, 2.38 – 2.41]. In the UK, National Grid, has replaced ACSR with GZTACSR resulting in a 130% increase in thermal rating [2.26]. Similarly, in Spain, GZTACSR has been used to increase thermal rating by 70% [2.39]. In Brazil, a 50% increase in thermal rating was achieved using TACSR and TACIR [2.38]. While, replacement by ACSS/TW in the USA resulted in a 70% increase in line rating [2.41]. Technical and financial evaluations of different HTLS conductors was carried out for projects in Romania [2.40] and Ireland [2.22] and recommended ACSS and GTACSR respectively.

2.5.1.2 Deterministic Method

By use of this method, current uprating can be achieved by increasing conductor temperature maintaining ground clearance. This technique makes use of weather conditions (wind speed, wind direction, ambient temperature, and solar radiation) to calculate current rating considering the maximum allowable conductor temperature [2.4]. Calculations can follow the methods recommended by IEEE [2.42] or CIGRE

[2.43] based on the worst-case weather condition for a line (high ambient temperature, low wind speed, full solar radiation and maximum load current). In this method, conductor temperature may exceed the design temperature resulting into conductor annealing and violation of safety clearance. Therefore, this method can only be used with proper analysis of risk due to high current. Provided with sufficient weather data of the area, an overhead line with low-rated temperature can be uprated using this method.

The templating temperature (temperature limit for a given clearance) can be increased by increasing conductor tension and conductor attachment height. This can be done by re-tensioning, using a negative sag device, extending line structures, using insulated cross-arms, and mid-span structures [2.3]. An example of the application of the deterministic method (re-tensioning and tower waist-extension) is described in a case study of a 138kV, double circuit line in Canada [2.44].

2.5.1.3 Probabilistic Method

In order to determine the risk of an unsafe condition occurring and to calculate the amount of time allowable for a conductor temperature to exceed its limit, the probabilistic method makes use of actual weather conditions of the geographical area where the line is located [2.4, 2.31]. An example of the application of this method to determine the probability of an unsafe condition for a given current value is given in [2.45], and different probabilistic methods are described in [2.46]. Using this method, the risk level can be kept constant at a defined exceedence level whilst varying the ampacity. The distribution of ampacity at different exceedence levels, various seasons or templating temperatures can also be determined [2.47].

2.5.1.4 Real-time Monitoring Method

In this method, the actual condition of the overhead line is monitored online. Actual conductor position is determined by measuring conductor tension, temperature, sag or the weather condition. Real-time monitoring helps system operators to develop and apply the line ratings in real time, based on actual conductor position. Various methods and new technologies are used for online condition monitoring of overhead lines. Weather stations, temperature sensors, load cells, cellular or radio communications, Geographic Positioning System (GPS) technology are some of the techniques used for line monitoring.

Using this method, conductor temperature rarely exceeds the design temperature and, hence, the risk of exceeding the annealing temperature of the aluminium is reduced [2.31]. In comparison with the rated capacity (static rating), this method provides higher line capability for 98% of the time and provides around 15% to 30% additional capability for over 95% of the time as can be seen in Figure 2.5 reproduced from [2.3]. This method was applied to obtain the dynamic thermal ratings of 400kV lines in Spain [2.48] and 115kV line in the USA by measuring ambient conditions in real time using weather stations [2.49]. A combination of a laser survey (for conductor catenary

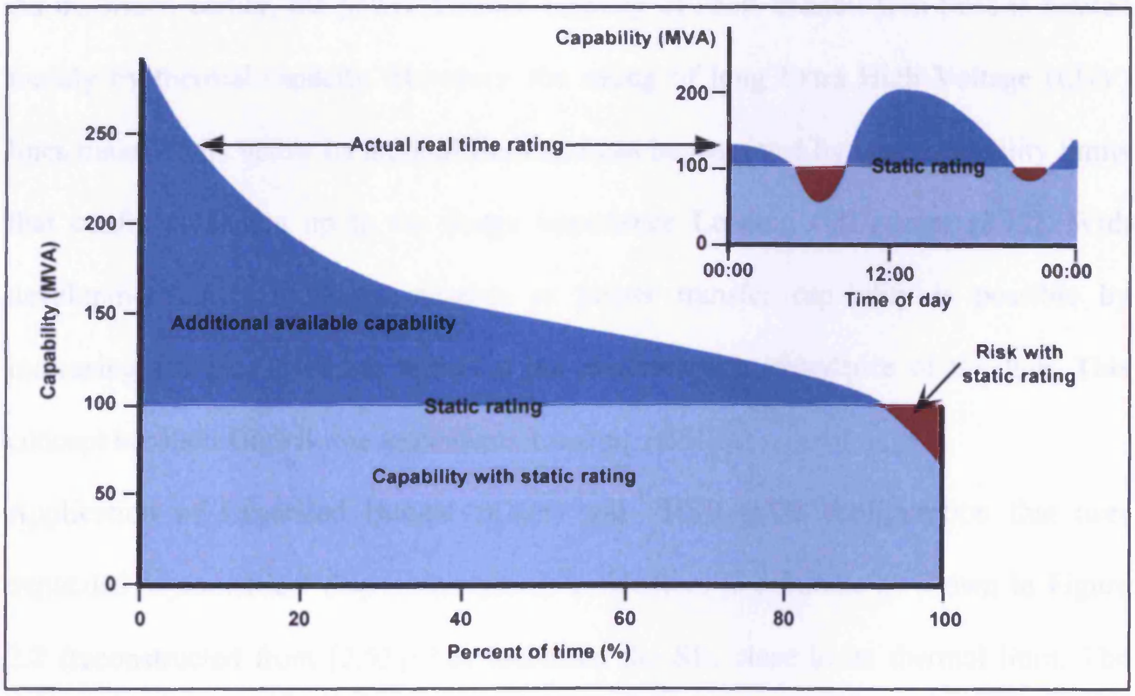


Figure 2.5: Additional available capability with overhead line monitoring real-time rating [2.3].

measurement), span-by-span sag adjustment and conductor temperature measurements were used to obtain a 30% increase in ampacity rating of a 230kV line in the USA [2.50]. Other examples of tension and sag measurement are described in [2.51] and [2.52]. Figure 2.6 illustrates some techniques used for real-time monitoring of overhead lines [2.3, 2.50].

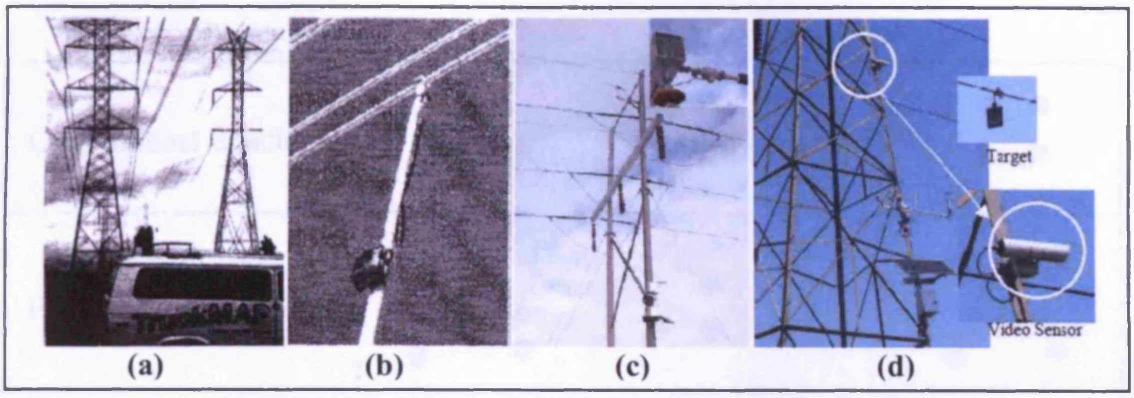


Figure 2.6: Techniques for real-time monitoring (a) Truck-based laser survey system [2.50] (b) Temperature measuring device on a 230kV line [2.50] (c) Conductor tension monitor [2.3] (d) conductor sag monitor [2.3].

2.5.1.5 High Surge Impedance Loading Method

As described earlier, the power transfer capacity of short transmission lines is limited mainly by thermal capacity. However, the rating of long Extra High Voltage (EHV) lines mainly falls below its thermal limit and can be restricted by system stability limits that confines loading up to the Surge Impedance Loading (SIL) level [2.12]. With development in technology, increase in power transfer capability is possible by increasing the SIL level i.e. lowering the characteristic impedance of the line. This concept is called High Surge Impedance Loading (HSIL).

Application of Expanded Bundle (EXB) and HSIL-EXB configuration that uses expanded asymmetrical disposition of sub-conductors in a bundle as shown in Figure 2.7 (reconstructed from [2.53]) has increased the SIL close to its thermal limit. The HSIL technique also helps to improve voltage regulation and can reduce the electric field intensity at the surface of the conductor [2.53]. A case study made on a 400kV quadruple bundle conductor line in India indicated 22% increase in SIL level with EXB configuration [2.12]. This improvement in SIL level increases transmission capacity of the line. As shown in Figure 2.8, HSIL/EXB technique has been adopted for uprating a 230kV and a 500kV line in Brazil [2.53, 2.54]. A 38% increase in transmission capacity was obtained for the 230kV line uprating.

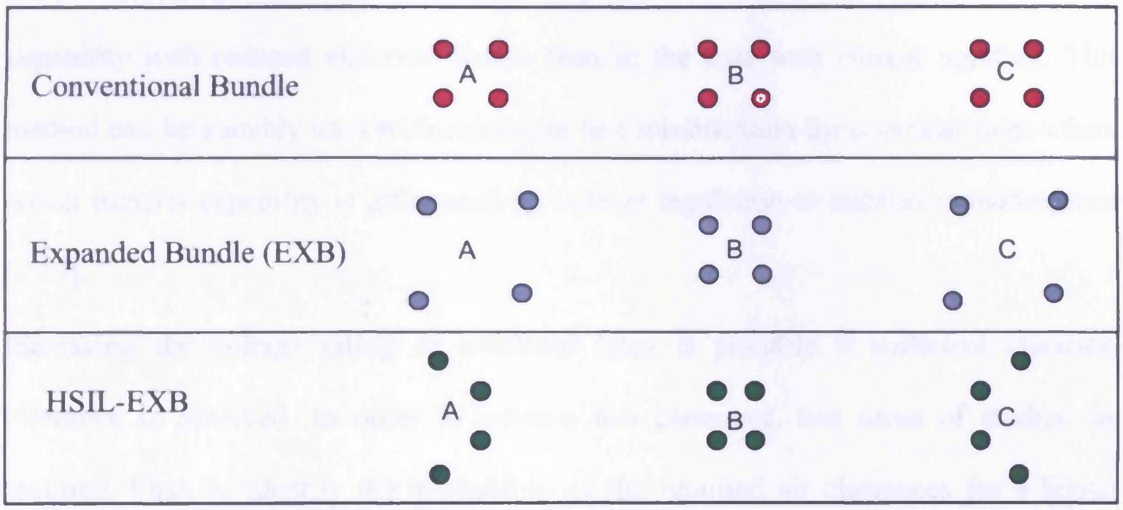


Figure 2.7: Cross section view of different bundle configurations used for increasing surge impedance loading (reconstructed from [2.53]).

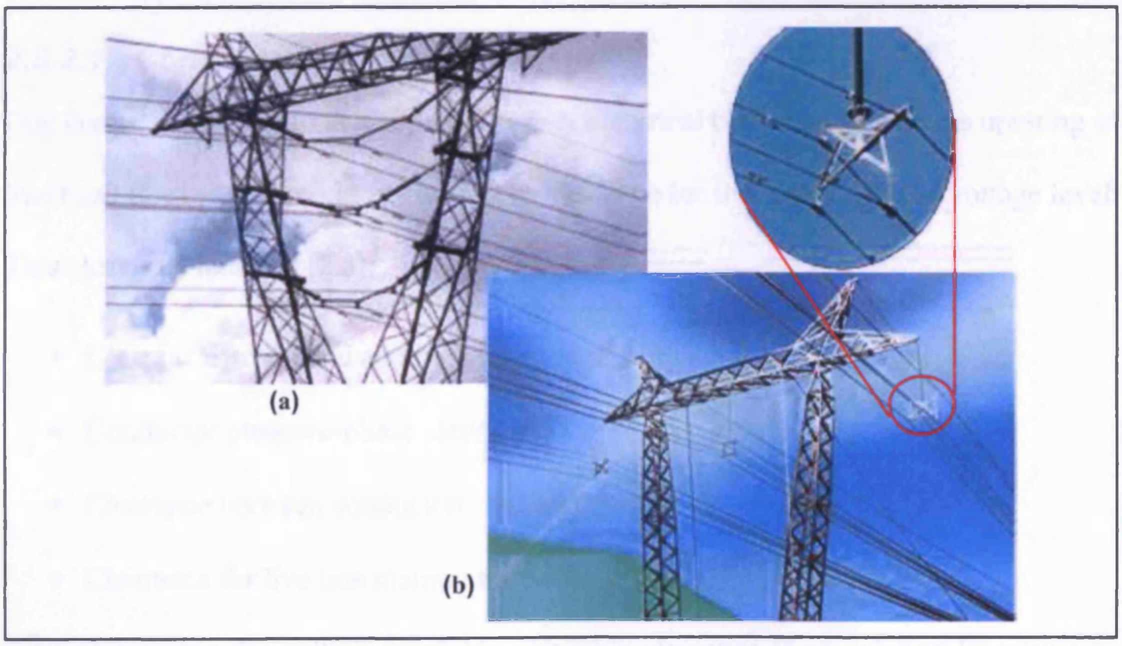


Figure 2.8: Lines in Brazil (a) 230kV HSIL line prototype [2.3] (b) 500kV HSIL-EXB line [2.53].

2.5.2 *Voltage Uprating*

Compared with current uprating, very few cases of uprating the line by increasing its voltage rating are found in the literature. According to a survey carried out by CIGRE [2.10], out of 40 uprating cases throughout the world, only 10 cases were found for voltage uprating. This may be because voltage uprating is more expensive than current uprating due to the requirement of modifications of terminal substation equipments. However, voltage uprating can potentially achieve much higher power transfer capability with reduced electrical losses than in the case with current uprating. This method can be suitably used with minimum line modification for overhead lines where power transfer capability is influenced by voltage regulation or stability considerations [2.13].

Increasing the voltage rating of overhead lines is possible if sufficient electrical clearance is achieved. In order to achieve this clearance, two areas of studies are required. First, to identify the availability of the required air clearances for a higher voltage in an existing structure and, second, to assess the insulation level required to withstand overvoltages due to power frequency, lightning impulse and switching surge.

2.5.2.1 Conductor Air Clearance

One common practice to achieve satisfactory electrical clearance for voltage uprating of overhead lines is to provide sufficient air clearance for the higher uprated voltage level. This clearance includes [2.3]:

- Clearances to ground and other supporting and adjacent structures
- Conductor phase-to-phase clearance
- Clearance between conductors and earth wires
- Clearance for live line maintenance

When increasing the voltage level, the available clearance in an existing line must be sufficient to withstand overvoltages with power frequency, switching and lightning activities at the uprated voltage level as stated in regulatory guidelines and industrial codes of practice. Different countries follow different guidelines for this purpose. For example, the National Electrical Safety Code (NESC) [2.55] applies in the USA whereas IEC 60071 [2.15, 2.19, 2.56] is used in Europe. In the UK, [1]BSEN 50341 [2.17, 2.18] and BSEN 50423 [2.57] are used together with IEC 60071 and an industry standard ENATS 43-8 [2.16]. These standards specify values of clearances for different overvoltage withstand levels (power frequency, lightning and switching). Table 2.3 shows the standard insulation levels for 275kV and 400kV nominal system voltages [2.15], and Table 2.4 compares electrical clearance requirements specified in IEC 60071-2 with those given in a National Grid standard [2.58] and ENA Technical Specification [2.16].

Table 2.3: Standard insulation levels for transmission systems [2.15]. Values in bold are standard withstand level considered for overhead line design in the UK.

Nominal Voltage (kV_{rms})	Highest System Voltage (kV_{rms})	Standard Switching Impulse Withstand Voltage			Standard Rated Lightning Impulse Withstand Voltage (kV_{peak})
		Longitudinal Insulation (kV_{peak})	Phase-to-earth (kV_{peak})	Phase-to-phase (ratio to the phase-to-earth peak value)	
275	300	750	750	1.50	850
					950
		750	**850**	1.50	950
					1050
400	420	850	850	1.60	1050
					1175
		950	950	1.50	1175
					1300
		950	**1050**	1.50	1300
					1425

[1] BSENs are English language version of European Standards (ENs)

Table 2.4: Comparison of withstand voltage and electrical clearance

Withstand Level (kV_{peak}) & Electrical Clearances (m)	For 275kV system (Highest system voltage : 300kV)			For 400kV system (Highest system voltage : 420kV)		
	IEC 60071 [2.15, 2.19]		UK standards [2.16, 2.58]	IEC 60071 [2.15, 2.19]		UK standards [2.16, 2.58]
	Min.	Max.		Min.	Max.	
Switching Impulse Level	750	850	850	850	1050	1050
Lightning Impulse Level	850	1050	1050	1050	1425	1425
Phase-to-earth Clearance	1.6*	1.8*	2.1	1.8*	2.6*	2.8
Phase-to-phase Clearance	2.3**	2.6**	2.4	2.9**	3.6**	3.6

Note: All clearances are based on switching impulse level. * conductor-structure, ** conductor-conductor

In most of cases, the opportunity to increase the voltage level of an overhead line is determined by phase-to-earth clearance. In some cases, it is also necessary to examine and satisfy the clearance requirements for particular weather conditions such as wind and snow.

Different techniques are used to increase conductor air clearance and these are described by *Daconti and Lawry* [2.13] :-

- For keeping appropriate conductor-to-ground clearances:
  - Re-tensioning the existing conductors
  - Performing sag adjustments (cutting out conductor lengths)
  - Increasing the conductor height at the attachment support (converting suspension strings to pseudo dead-end string)
  - Increasing the attachment support height
  - Raising and / or moving towers
  - Inserting additional towers
  - Performing terrain contouring in rural areas
- Different line compaction techniques for adjusting phase-to-phase clearance:
  - Reducing distance between phase conductors

- Increasing distance between subconductors in a bundle

- Converting low voltage double circuit line to high voltage single circuit line
- Application of V-string insulators to prevent swinging of suspension strings

Examples of structural extension for achieving appropriate conductor air clearance for cases of voltage uprating in the USA are described in [2.59 – 2.61]. In Japan, insulator-supported jumper devices and compact phase-to-phase spacers were developed for ensuring clearances for the uprating of a 66kV line to 154kV operation [2.30]. Other examples of application of phase-to-phase spacers are in use in Canada, Germany and the USA [2.3, 2.29] while composite insulators were used in Brazil for a compact line solution of voltage uprating [2.62]. The American Electric Power Company has introduced an outward extending conductor loop, named "Upgrade-Loop" for increasing electrical clearances of conductors from ground and tower structure without any modification in the existing structures [2.63]. Figure 2.9 shows examples of different techniques applied for ensuring electrical clearance in overhead lines.

CIGRE Technical Brochure 294 [2.10] describes a project where increased clearance was achieved in uprating a 69kV double circuit line to a single circuit 138kV line in

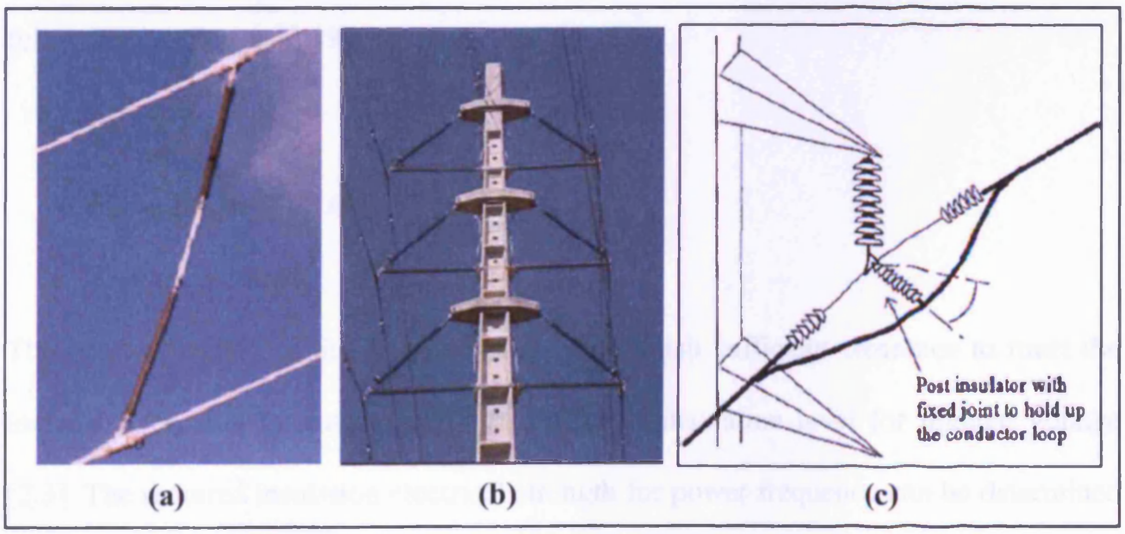


Figure 2.9: Different techniques for ensuring conductor air clearance (a) phase-to-phase spacer in 161kV line [2.3] (b) insulating crossarm in 230kV line [2.62] (c) view of an Upgrade-Loop [2.63].

Brazil and, [2.5] describes application of a V-string insulator for uprating a 275kV line to 400kV in South Africa, as shown in Figure 2.10.

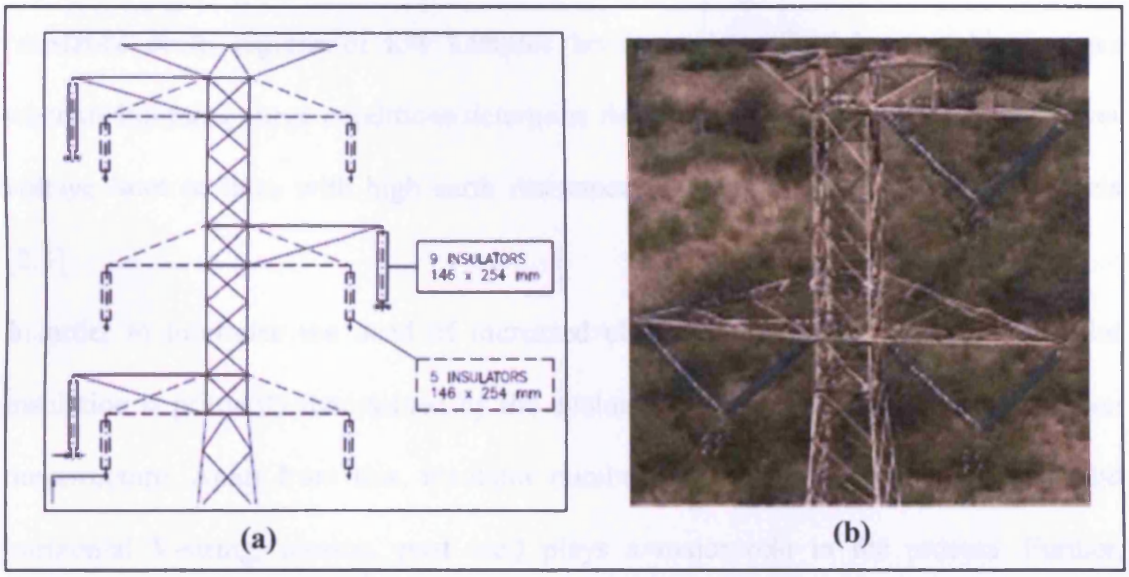


Figure 2.10: (a) uprating 69kV double circuit line to 138kV single circuit line in Brazil [2.10] (b) use of V-string insulator for uprating 275kV line to 400kV in South Africa [2.5].

2.5.2.2 Insulation Electrical Strength

Another solution to achieve adequate electrical clearance is through the evaluation of electrical strength of available insulation. Determining the actual strength of the insulators of an overhead line requires assessment of voltage stresses under the following conditions [2.19]:

- Power frequency,
- Lightning impulse and,
- Switching surges

The basic objective of the assessment is to establish sufficient clearance to meet the increased required minimum creepage and basic insulation level for uprated voltage [2.3]. The required insulation electrical strength for power frequency can be determined by evaluating the insulation level based on a pollution level that determines the minimum required creepage for insulators. IEC 60815 [2.64] defines different Site Pollution Severity (SPS) classes and specifies specific creepage for each class.

The required insulation strength for higher voltage lines or lines with low earth resistance or in regions of low keraunic levels is determined by switching surges whereas lightning surge conditions determine the required insulation strength for lower voltage lines or lines with high earth resistance or in regions of high keraunic levels [2.3].

In order to minimise the need of increased clearances, the selection of a particular insulation is primarily determined by the evaluation of the conductor configuration on the structure. Apart from this, insulator numbers and geometry (I-strut, vertical and horizontal V-string, tension, post etc.) plays a major role in the process. Further, climatic factors such as air density, humidity, precipitation, pollution, temperature and, ice deposition have to be considered [2.3].

Re-insulation is the fundamental technique used for ensuring insulation electrical strength for voltage uprating. This technique includes adding or substituting insulators, replacing standard insulators by polymeric or anti-fog units, I-string converted to V-strings and in some cases use of insulated cross-arms [2.13]. Examples of application of these techniques for voltage uprating in countries such as South Africa, USA, Brazil, and Australia are described in [2.5, 2.59, 2.62, 2.65].

2.5.3 Supplementary Methods

Other methods to increase power transfer capability of their overhead lines are as follows:

- Conversion of 3-phase line to multiphase (> 3-phase) line
- HVAC line to HVDC line
- HVAC line to hybrid AC-DC line

Research was carried out to investigate multiphase technology for enhancement of power transfer capability of overhead lines and 6-phase and 12-phase technology were found quite promising [2.66]. A study of a 138kV double circuit, 3-phase line in the USA showed the possibility of uprating the line to 6-phase operation without degrading its reliability and environmental performance [2.67]. However, this method is not widely adopted due to comparatively high cost of changes in the substation equipments and layout than any other uprating method. Further, multiphase operation of a 3-phase system produces additional audible noise, radio noise and increases electric field magnitude at ground level [2.67]. Therefore the method is not suitable for any line passing through an urban area.

Existing AC lines may also be converted to transmit DC power for increasing power transfer capability of overhead lines with advantages for stability, controlled emergency support and no contribution to short circuit level. Research shows significant enhancements in power transfer capacity by converting AC lines to bipolar or monopolar DC operation. A study in Spain indicated that, up to 175% increase in capacity was possible without any change of line components while a 500% increase was achieved with 6 crossarm in AC system modified to 2, longer and stronger crossarm, and with replacing I-string insulators to V-string [2.68]. Similarly, [2.69] demonstrates the possibility of a 350% increase in transmission capacity by converting an AC line to HVDC.

Recently, a new concept of a hybrid AC-DC power transmission as shown in Figure 2.11 has been proposed for uprating overhead lines and involves simultaneous AC-DC power transmission in a same line. Studies made in Sweden [2.70] and in India [2.71] demonstrate the feasibility of converting double circuit AC lines into AC-DC composite lines by utilising one of the circuits as a bipolar DC without any major alteration to the existing structure. The Indian study [2.71] demonstrated that an 83% increase in line capacity was achievable.

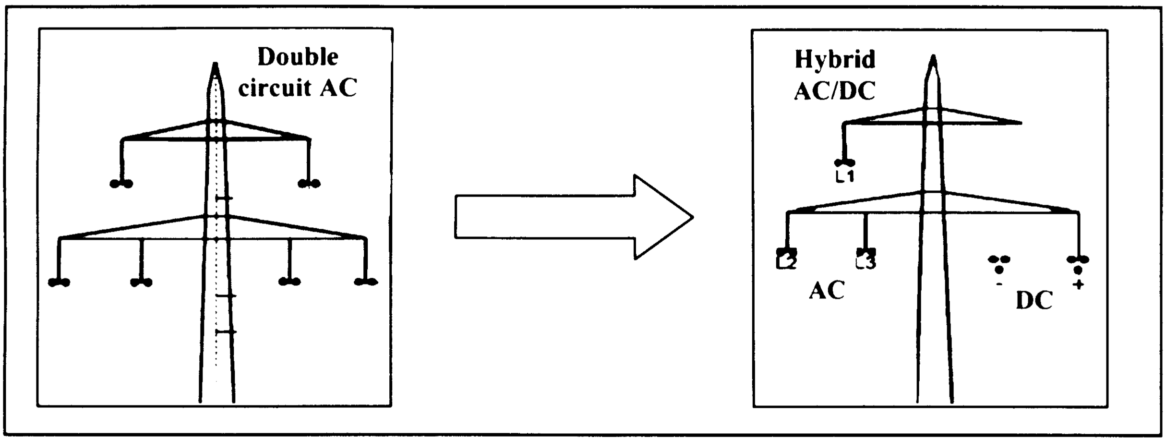


Figure 2.11: Conversion of double circuit AC line to hybrid AC/DC line [2.70].

2.6 ENVIRONMENTAL IMPACTS OF UPRATING

There are various environmental impacts of overhead lines. A survey by EPRI showed that the majority of people oppose overhead lines due to visual effect, property devaluation and concern about health and safety [2.8]. While uprating where existing lines are still in use, the visual impact remains the same. However, the health and safety issue is associated with the electric and magnetic fields, and these will be affected by uprating.

The voltage uprating may be limited to certain extent by an increase in electrical field magnitudes, resulting in the risk of corona effect, whereas an increase in magnetic field can limit the current uprating process. Without the change in conductor coordinates, the increase in the nominal voltage leads to an increase of the electric field in the surroundings. The Electrical field, if higher than threshold, starts producing corona resulting in audio noise, visible light and radio interference. Also, the change in conductor coordinates during voltage uprating has a significant effect on magnetic fields produced around the line. The electromagnetic field issue, therefore, should be analysed when uprating voltage or current to ensure that electric and magnetic fields values are within the limits dictated by different guidelines. In the UK, National Radiological Protection Board (NRPB) specifies limits of exposure to electromagnetic fields [2.72] and adopts the guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [2.73] and supports the recommendation of the Council of the European Union (CEU) [2.74] on limiting exposure of the general public. With reference to these guidelines, National Grid [2.75] lists the exposure limits of electric and magnetic fields (higher than ICNIRP limits) applicable in the UK, as shown in Table 2.5. The ICNIRP and National Grid limits will be compared in Chapter 7. Typical ground-level UK field levels from overhead power lines of different voltage levels are shown in Table 2.6 [2.76].

Table 2.5: Electric and magnetic field exposure limits applicable in the UK [2.75].

Public Exposure		Occupational Exposure	
Electric Field	Magnetic Field	Electric Field	Magnetic Field
9 kV/m	360 μT	46 kV/m	1800 μT

Table 2.6: Typical ground-level UK field levels from overhead power lines of different voltage levels [2.76].

Overhead Lines Voltage Level	Field	Electric Field (kV/m)	Magnetic Field (μT)
The largest steel pylons (275kV & 400kV)	Maximum field (under line)	11	100
	Typical field (under line)	3 – 5	5 – 10
	Typical field (25m to side)	0.2 – 0.5	1 – 2
Smallest steel pylons and largest wooden poles (132kV)	Maximum field (under line)	4	40
	Typical field (under line)	1 – 2	0.5 – 2
	Typical field (25m to side)	0.1 – 0.2	0.05 – 0.2
Wooden poles (11kV & 33kV)	Maximum field (under line)	0.7	7
	Typical field (under line)	0.2	0.2 – 0.5
	Typical field (25m to side)	0.01 – 0.02	0.01 – 0.05

The electric and magnetic fields produced around a line are determined by parameters such as operating voltage, conductor spacing, diameters, bundle configuration, and the number of sub-conductors in the bundle. Table 2.7 shows the effect of adjustments to line geometry on different environmental issues [2.3].

Table 2.7: Influence of different parameters [2.3].

Parameter		Electric Field	Magnetic Fields	Radio Interfere nce	Audio Noise
Phase-to-phase clearance	↑	↑	↑	↘	↓
Conductor height above ground	↑	↓	↓	↘	↘
Number of sub-conductors (for a given total cross-section)	↑	↑	=	↓	↓
Sub-conductor spacing	↑	↗	=	↗	↗
Total conductor cross-section	↑	↗	=	↘	↘

↑ Strong increase ↓ Strong decrease

↗ Slight increase ↘ Slight decrease = No significant effect

Techniques can be used to minimise the electric and magnetic fields while uprating overhead lines. The use of bundled conductors or modifying the bundle configuration can help in reducing both electric and magnetic field effects together with considerable reduction in audio noise. Conversion of low voltage multi-circuit (more than two circuit) line to high voltage single or double circuit line can help voltage uprating with less audio noise. In Germany, a four-circuit 220kV twin bundle line was converted to a two-circuit 380kV triple bundle and a two-circuit 220kV twin bundle line to double the power transfer capability [2.77]. Likewise, radio interference and audio noise were minimised by uprating a 3-phase double circuit line by converting it into a 6-phase single circuit line [2.67].

2.7 CHARACTERISTICS OF OVERHEAD LINE UPRATING WORKS IN DIFFERENT COUNTRIES

Overhead line uprating work has been carried out in different countries around the globe. The necessity of increasing utilisation of existing overhead line was realised in the fifties. In 1955; Ontario Hydro in Canada uprated 50 miles of an existing 115kV wood pole line for operation at 230kV by simply adding two insulator units in existing strings [2.78]. In the mid sixties, various utilities in the USA carried out experimental and investigative work to identify possibility of uprating their lines [2.79, 2.80]. In mid sixties, in Canada, Otter Tail Power Company in the United States carried out uprating a 90 miles section of a 115kV wood pole line to 230kV operation [2.7]. Since then, various cases of uprating overhead lines are found. However, literatures show that the uprating works were extensively carried out only after late eighties.

Based on the responses to the questionnaire sent abroad, CIGRE Working Group B2.06 [2.10] was able to collect and compare practices and experiences of uprating / upgrading project in 20 different countries. In addition to that, several uprating projects in other different countries were found. Summary of the uprating works listed in CIGRE Technical Brochure 294 [2.10] and other literatures are presented here in alphabetical order of country name.

In Australia, different methods of uprating are used to achieve greater line ratings. In the past, 33kV and 66kV lines were uprated to 110kV and 132kV. Synthetic composite line post insulators were used [2.65]. In recent years, a few 330kV lines were uprated and various 66kV and 330kV lines are proposed to uprate to 132kV and 500kV respectively [2.81, 2.82]. Similarly, to compensate high summer demand, a few 132kV lines were proposed for uprating by increasing conductor operating temperatures (49 °C to 60 °C to 75 °C) with a small number of replacement of existing structures [2.83, 2.84].

In Belgium, during the period 1999-2002, 10 lines were thermally uprated by increasing the thermal rating from 40 °C to 75 °C [2.10]. Copper conductors were replaced with AAAC conductors of similar weight. In recent years, various lines are examined for the possibility of uprating, and a few 220kV lines are proposed to uprate its thermal ratings.

In Brazil, many cases of voltage and thermal uprating were found. Converting 69kV double circuit line to 138kV single circuit line by regrouping the same conductors in twin bundle has helped increase the line capacity at relatively low cost [2.10]. A 50% increase in line capacity was obtained by replacing ACSR conductors with high temperature low sag conductors (TACSR) [2.38]. In recent years, use of composite insulators and EXB technologies are used in increasing transfer capacity of 230kV and 500kV lines [2.53, 2.62].

As mentioned earlier, Canada has long history of uprating overhead lines. In recent years, this work is more focussed on reliability issues due to failures caused by ice loading [2.10]. Therefore, utilities are more focussed on upgrading rather than uprating their lines. However, a few cases of current uprating of 230kV line by replacing ACSR conductors with ACSS conductors with some structural modifications are known [2.10].

In France, during the early eighties, a 30kV overhead line built in late fifties was converted to 90kV by use of aluminium alloy conductors and triangular conductor configuration for sufficient clearance. The transmission capacity increased 9 times together with 300% increase in thermal capability [2.85].

A 220kV four-circuit line installed in 1965 in Germany had its transmission capacity increased by approximately 1600MW by converting it into two 380kV and two 110kV circuits. In this case, twin bundle ACSR 240/40 conductors were replaced by triple bundle ACSR 380/50 conductors [2.77]. Replacing twin bundle with quadruple bundle conductors has helped increasing the capacity by 31% and considerable reduction in corona and audible noise [2.77].

In Italy, uprating of a few 70kV and 132kV lines were possible by reconductoring with new conductors with high cross sectional area [2.10].

Requirement of uprating more than 1000 km of 220kV network in Ireland is identified. Investigation showed that the HTLS conductor (GTACSR) is preferred and could be utilised to uprate the existing 220kV network [2.22].

A pilot uprating project of a few 161kV lines in Israel was carried out in the year 2000. The ampacity of the line with existing ACSR and AAAC conductors was limited by ground clearance. Two methods of uprating were chosen. First is to toughen conductor tension and second is to shorten the suspension lowering the conductor under the crossarm of a suspension pole by replacing porcelain insulators with shorter synthetic ones or moving to V-shaped suspension insulators [2.28].

For use of existing 66kV lines for 154kV operation in Japan, insulator-supported jumper devices to increase conductor-to-tower clearance and compact phase-to-phase spacers to increase phase-to-phase clearance at higher voltage level were used [2.30]. Line compaction with the application of these devices helped to increase the transmission capacity together with improved magnetic field in the surroundings.

In Norway, several 132kV double-circuit lines were converted to single-circuit 300kV line. Transmission capacity was increased four times by using original conductors in twin bundle configuration [2.10].

Transmission capacity of a 220kV line in Poland was doubled by use of reconductoring techniques of uprating [2.10]. Existing ACSR conductors operating at 55°C was replaced by HTLS conductors operating at 106°C.

For uprating 220kV double circuit line with ACSR conductor in Romania, after thorough analysis of different HTLS conductors, ACSS conductor was found suitable from technical and economical point of view [2.40]. ACSS conductor was found cheap and it considerably reduced power losses in the system thereby minimising the cost. Similarly, in Serbia and Montenegro, replacing existing conductors with conductors of large cross sectional area, helped with thermal uprating of 110kV lines [2.10].

In South Africa, cases of uprating 66kV, 275kV and 400kV lines were cited [2.5, 2.10, 2.27]. Thermal uprating of 275kV and 400kV lines was done by increasing templating temperature. Airborne Laser Survey was carried out on the entire line and a PLS-CADD model was built to determine the real position of the conductors [2.27]. Increasing the rating of a 275kV line to 400kV was possible by re-insulation [2.5]. It mainly involved the replacement of existing U120 and U135 type cup-and-pin insulators with U160 type glass insulators having high specific creepage and similar diameter. In order to obtain required conductor-to-earth clearance, insulation in central phase was changed to V-String assembly. Similarly, uprating 66kV line to 132kV was possible with modifications to the attachment and insulation of the existing structures [2.10].

In Spain, many 220kV and 400kV lines were uprated by increasing templating temperature from 50 °C to 80 °C with power increase from 30% to 50% [2.10]. In the 400kV ring of Madrid, a dynamic thermal rating was obtained in real-time by using weather stations [2.48]. A study on Alcira-Gandia, 132kV line in Spain shows the possibility of increasing ampacity rating by 70% with the use of HTLS conductors [2.39, 2.86].

Several lines built during the fifties and sixties in the United Kingdom were uprated during late eighties and nineties. In 1986, a 275kV interconnection between Scotland and England was uprated to 400kV operation [2.87, 2.88]. The transmission capacity of a number of lines in England and Wales are limited due to insufficient thermal capacity. It has been possible to uprate some ACSR lines from 50 °C to 75 °C with an increase in rating by nearly 25% [2.32]. Further improvement in line rating (up to 130% compared to original ACSR conductor) was obtained by application of gap type ACSR (GZTACSR) conductors in existing 275kV and 400kV systems [2.26].

In recent year, Ofgem has identified two interconnections between England and Scotland to be uprated for wholesale electricity market. Further, requirement for voltage uprating of existing overhead lines are identified. To compensate the impact of connecting additional generation in the existing system, it is proposed to increase transmission capacity by uprating the existing double circuit 275kV line between Blyth to Hawthorn Pit substations along the North East coast of England [2.89]. Uprating 275kV Stella West to Spennymoor overhead line to 400kV is due to commence in October 2011 [2.89].

Over the last 55 years, substantial cases of increase in the transmission capacity of overhead lines in the United States of America were reported. Range of techniques for current and voltage uprating was used. Otter Tail Power Company has performed several investigative works and have experience of uprating their overhead lines [2.29, 2.61]. 'Sargent & Lundy', has provided numerous engineering services to different companies in the USA for uprating their overhead lines. These include uprating 69kV to 138kV by replacing copper conductor with ACSR conductors [2.60], 115kV double circuit uprating to 230kV using different voltage uprating techniques [2.59] and several other thermal and voltage uprating projects on 46kV, 138kV, 161kV and 230kV overhead lines [2.90].

2.8 CONCLUSIONS

In this chapter, an extensive literature review on uprating overhead lines was carried out with particular focus on techniques of current and voltage uprating. The demarcation between 'uprating' and other options of increased utilisation of overhead line was clarified. Uprating of overhead lines is considered as "increasing its MVA capacity without any wholesale structural modifications, reconstruction, or replacement of existing structures".

Constraints for increasing power transfer capability were described. It was shown that increasing power transfer capability by increasing current rating is mainly related to the conductor thermal limit. However, increasing voltage level of the line is limited by constraints related to overvoltage, electrical clearances, insulation levels, structural design and other environmental impacts such as electromagnetic field and audio noise.

To increase the capacity of the line, it is important to decide whether to build a new line or to uprate the existing line. The decision making process is influenced by technical, institutional and financial issues. A review of several cases in which these issues had influenced the decision making process revealed that institutional and financial constraints play a decisive role. The current-uprating process being comparatively cheaper than voltage-uprating, in the review process, more cases of current-uprating were identified than for voltage-uprating.

Different methods and techniques for uprating overhead lines were reviewed. Current-uprated line used new conductors, online condition monitoring techniques and, improved line surge impedance level to achieve adequate thermal limit whereas, voltage-uprated lines used insulating crossarm, inter-phase spaces, new insulators and crossarm modifications to achieve adequate air clearance and insulation electrical strength. It was found that the techniques suitable for uprating overhead lines differ case to case. The selection of a particular technique depends upon the line's electrical parameters together with its physical and surrounding environmental conditions. It is, therefore, difficult to develop a common technique applicable to uprate all kinds of overhead lines. A separate study of each case is necessary to decide for any technically and economically feasible method of uprating.

CHAPTER 3

IMPORTANT ASPECTS OF INSULATION COORDINATION FOR VOLTAGE UPRATING

3.1 INTRODUCTION

Insulation coordination, according to IEC 60071-1 [3.1], is defined as "*selection of the dielectric strength of equipment in relation to the operating voltages and overvoltages which can appear on the system for which the equipment is intended and taking into account the service environment and the characteristics of the available preventing and protective devices*". The objective of insulation coordination is to ensure that any insulation failure is self-restoring and the failure probability to fall within the acceptable limit. Insulation coordination of overhead lines is based on the estimation of most severe overvoltage produced due to power frequency, switching and lightning activities which then is used to determine maximum temporary, slow front and fast front overvoltages respectively. These overvoltages are then related to the insulation breakdown characteristics through relevant margins to obtain withstand voltages for the network components for a given statistical risk of insulation failure. The withstand voltage is then used to identify the minimum electrical clearance requirement and the insulation electrical strength.

The uprating process requires the study of insulation coordination of overhead lines at its voltage rating based on combined consideration of stress applied to the line and its electrical strength. In this chapter, insulation coordination for voltage uprating is theoretically analysed. The insulation coordination process is explained for transient and temporary overvoltages so that the risk of failure can be determined. The values and relevant equations derived from different international and British standards such as

IEC 60071 [3.1 – 3.3], IEC 61865 [3.4], BSEN 50341 [3.5, 3.6], and BSEN 50423 [3.7] are used to calculate and compare electrical clearance distances for standard insulation levels under different overvoltages. Finally, insulation levels of overhead lines are assessed based on different pollution levels.

3.2 OVERVOLTAGES

Overvoltages in overhead transmission and distribution systems are generated due to sudden changes in operating conditions. These changes are due to switching operations, lightning strokes or faults in the system. The magnitude of these generated overvoltages are key for determining the voltage rating of system components, their risk of failure and the selection of the required withstand level for equipment as well as air gap insulation for transmission and distribution towers / poles. A methodical analysis of overvoltages on the existing system is required so that the possibility of choosing a reduced withstand voltage level can be explored, thereby, achieving a reduced clearance level, noting also that the shape of overvoltage across the air gap determines the dielectric strength of the gap. With reference to Figure 3.1 [3.3], IEC 60071-4 classifies overvoltages as;

- Temporary overvoltages,
- Slow-front overvoltages and,
- Fast-front overvoltages

In the voltage uprating process, consideration of slow-front and fast-front overvoltages are more important to identify the additional air clearance requirements for uprated voltage. The influence of a particular overvoltage in the process depends on several parameters such as line voltage level, earth resistance, and keraunic level of the area where the line is located. Table 3.1 shows the classes and shapes of different overvoltages [3.3].

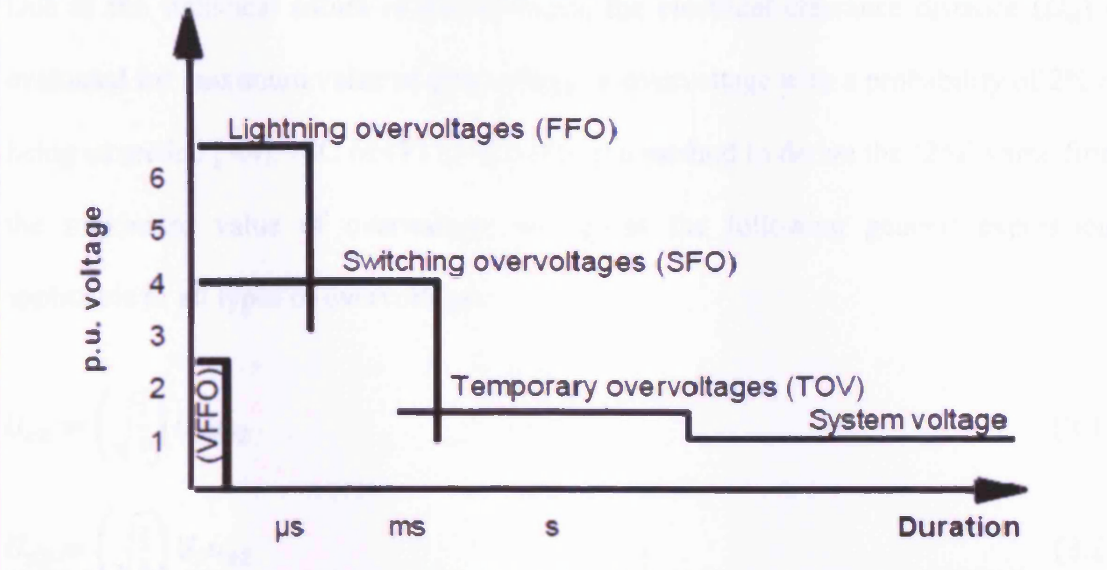
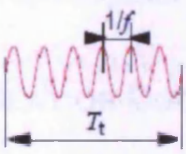
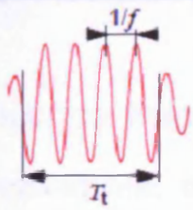
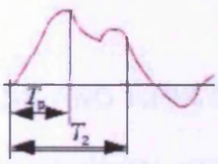
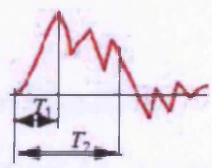
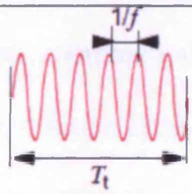
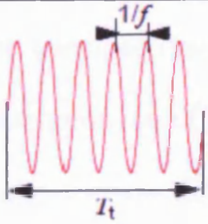
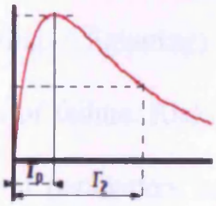
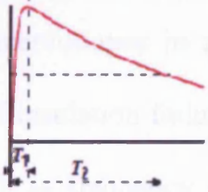


Figure 3.1: Overvoltages types [3.3].

Table 3.1: Different overvoltage shapes and their standard shapes [3.3].

Class	Low Frequency		Transient	
	Continuous	Temporary	Slow-front	Fast-front
Voltage or Overvoltage Shapes	 f = 50 Hz or 60 Hz $T_t \geq$3 600 s	 10 Hz < f < 500 Hz 0,03 s $\leq T_t$ $\leq$ 3 600 s	 20 µs < T_p $\leq$ 5 000 µs $T_2 \leq$ 20 ms	 0,1 µs < T_1 $\leq$ 20 µs $T_2 \leq$ 300 µs
Standard Voltage Shapes	 f = 50 Hz or 60 Hz T_t : to be specified	 48 Hz $\leq f$ $\leq$ 62 Hz T_t = 60 s	 T_p = 250 µs T_2 = 2 500 µs	 T_1 = 1,2 µs T_2 = 50 µs

Due to the statistical nature of overvoltages, the electrical clearance distance (D_{el}) is evaluated for maximum value of overvoltage or overvoltage with a probability of 2% of being exceeded [3.4]. IEC 61472 [3.8] outlines a method to derive the '2%' value from the maximum value of overvoltage and gives the following general expressions applicable to all types of overvoltages.

$$U_{e2} = \left(\sqrt{\frac{2}{3}}\right) U_s u_{e2} \tag{3.1}$$

$$U_{p2} = \left(\sqrt{\frac{2}{3}}\right) U_s u_{p2} \tag{3.2}$$

Where,

- U_{e2} and U_{p2} are phase-to-earth and phase-to-phase statistical overvoltage (2% overvoltage) respectively; and u_{e2} and u_{p2} are their corresponding values in per unit.
- U_S is the highest system voltage.

3.3 Insulation Coordination Process and Risk of Failure

For voltage uprating of an overhead line, the overvoltages generated by different sources each have a significant role in defining the withstand voltage level and corresponding required electrical distance (D_{el}).

3.3.1 Transient Overvoltage and Risk of Failure Concept

The insulation coordination for transient (switching / lightning) overvoltages in an overhead line is based on the determination of risk of failure. Risk of insulation failure due to transient overvoltage depends upon different parameters such as frequency of occurrence of the transient phenomenon, the overvoltage probability of this event and the probability of insulation failure [3.2]. If the probability of occurrence of overvoltage (stress) is defined by *P(x)* and the insulation failure (strength) probability by *P(y)*, then the risk of failure *(R)* of the insulation is obtained by multiplying stress and strength as given in Equation (3.3).

$$R = P(x) \times P(y) \tag{3.3}$$

Overvoltages in the line are random phenomena and, hence, presented statistically in terms of a frequency distribution function $f\ (V)$. In this case, the probability of occurrence of overvoltages in a small voltage interval dV is:

$$P(x) = f(V)\, dV \tag{3.4}$$

Here, insulation failure probability, $P(y)$, for an impulse value of V becomes $P(V)$ presenting the risk of failure for small interval as:

$$dR = f(V)\, P(V)\, dV \tag{3.5}$$

Now, the total risk of failure (R) in an insulator due to the entire range of overvoltage magnitude is given by integrating Equation (3.5) which is presented in Equation (3.6).

$$R = \int_{0}^{x} f(V)\, .\, P(V)\, dV \tag{3.6}$$

Figure 3.2 illustrates the risk of failure. In this figure, the shaded area represents the risk of failure which is obtained by multiplying two curves representing frequency distribution of overvoltage and the probability of insulation failure. The insulation coordination for transient overvoltage for any electrical system is based on these curves. A simplified statistical method of insulation coordination for switching overvoltages as stated in IEC 60071-2 defines the distribution of overvoltages and insulation strength by points on each of the curves represented by $f\,(V)$ and $P(V)$ as shown in Figure 3.2. The risk of failure in an insulation is unavoidable because it is impossible to obtain suitable

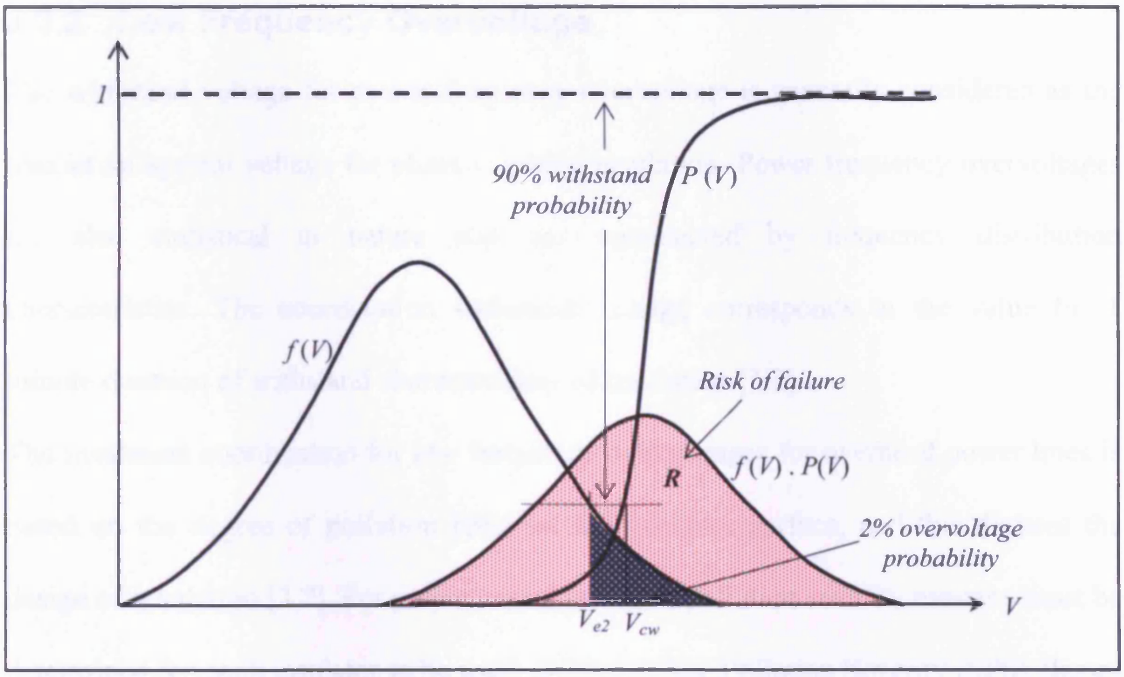


Figure 3.2: Evaluation of risk of failure for insulation coordination.

insulation such that the $f(V)$ and $P(V)$ do not overlap. Therefore, the insulation is selected such that the 2% overvoltage probability (denoted by V_{e2} on $f(V)$, known as 'coordination overvoltage') coincides with the 90% withstand (10% failure) probability (denoted by V_{cw} on $P(V)$, known as 'coordination withstand voltage') as recommended by IEC and shown in Figure 3.2. With the insulation coordination for lightning overvoltages, the frequency distribution of overvoltage is calculated by dividing the return rate by the total number of overvoltages and the distribution function, $f(V)$, is obtained by the derivative of the result so that risk of failure is calculated using Equation (3.6) [3.2].

The probability of occurrence of overvoltage can be minimised by different overvoltage control techniques and the minimum required insulation withstand level can be changed by use of appropriate insulation in the line. Therefore, the control of these parameters represented by the f (V) and $P(V)$ curve in Figure 3.2 can solve different technical issues for voltage uprating and, hence, the control may possibly produce the opportunity for voltage uprating of overhead lines.

3.3.2 Low Frequency Overvoltage

The withstand voltage for power frequency overvoltage is generally considered as the maximum system voltage for phase-to-phase insulation. Power frequency overvoltages are also statistical in nature and are represented by frequency distribution characteristics. The coordination withstand voltage corresponds to the value for 1 minute duration of withstand characteristics of insulation [3.2].

The insulation coordination for low frequency overvoltages for overhead power lines is based on the degree of pollution level on the insulator surface, and this dictates the design of insulation [3.2]. For proper coordination, a pollution severity measure must be determined for each insulator to be used. Different Site Pollution Severity (SPS) classes with their specific creepages as defined in IEC 60815 [3.9, 3.10] and the effect of pollution on insulation strength will be explained in detail in Section 3.7.

3.4 Clearance Envelope

As previously stated, overhead line insulation is subjected to different types of overvoltages produced as a result of power frequency, lightning and switching phenomena. Each class of overvoltage must be considered separately to assess the possibility of voltage uprating which requires confirmation of available electrical clearance. The electrical clearance requirements for a particular line voltage level are derived from fundamental breakdown voltage characteristics which determine the required clearance envelope for power frequency, lightning and switching overvoltages. The geometry of these clearance envelopes is influenced by the insulator swing angle due to wind in the case of both power frequency and switching conditions [3.11]. In the case of a lightning surge, it also depends on the nature of the backflashovers on the line. The clearance envelopes for an overhead transmission line under different overvoltages are shown in Figure 3.3, reproduced from [3.11].

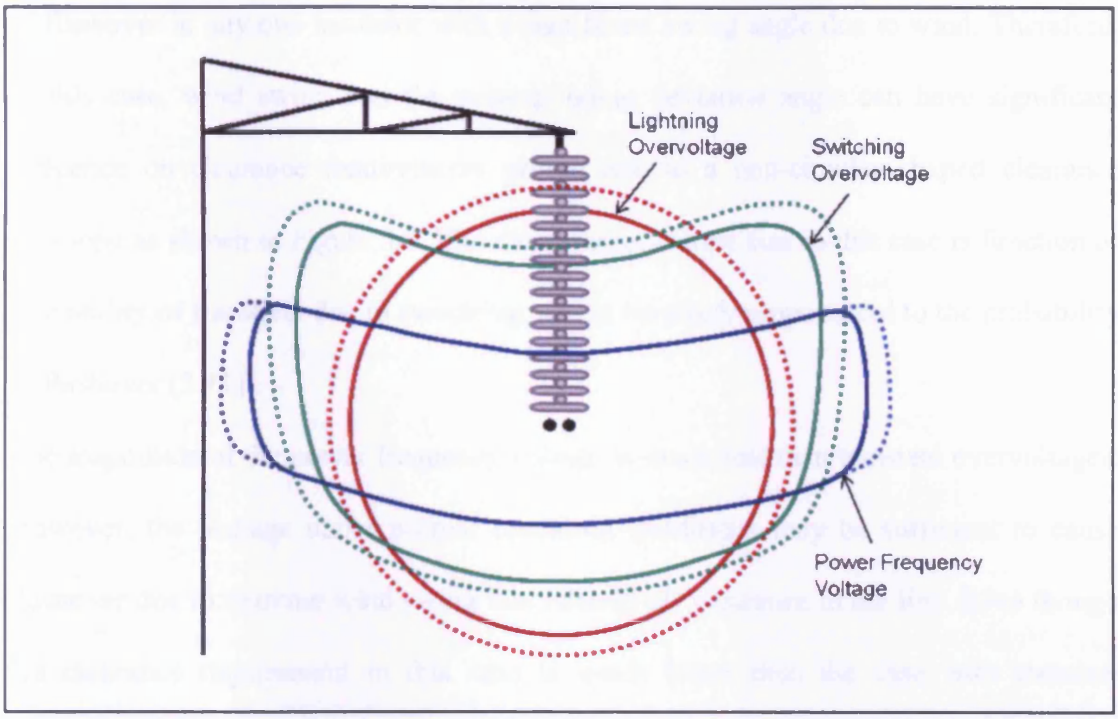


Figure 3.3: Electrical clearance envelope for different overvoltages (reproduced from [3.11]). Dotted lines show envelope for lower flashover rate (lightning), lower flashover probability (switching) and higher pollution level (power frequency).

In the case of a lightning stroke hitting the earth wire, the distance that the surge travels along the line is less with towers of low footing resistance (normally < 30 Ω). Therefore, under such conditions overvoltages are likely to occur at towers near to the stroke position. On the other hand, it is very unlikely to have wind conditions that produce a large swing angle exactly at the time of stroke and around the striking area [3.5]. Therefore, the effect of swing angle under lightning is neglected. As a result, the ideal geometry of the electrical clearance envelope for lighting overvoltage is circular in shape as shown in Figure 3.3. The radius of this circular envelope is a function of the flashover rate (flashes/100km/per year) and the radius of the circle is inversely proportional to the flashover rate [3.11].

Unlike lighting surge propagation along the earth wire, a switching surge voltage can travel a long distance along the line with relatively little attenuation. This results in stress applied to multiple towers along the line. Due to this, there is a higher possibility of flashover in any one insulator with a significant swing angle due to wind. Therefore, in this case, wind swing and the corresponding deviation angle can have significant influence on clearance requirements giving rise to a non-circular shaped clearance envelope as shown in Figure 3.3. The clearance envelope size in this case is function of probability of flashover due to switching, and is inversely proportional to the probability of flashover [3.11].

The magnitude of the power frequency voltage is much less than transient overvoltages. However, the voltage under normal operating conditions may be sufficient to cause flashover due to extreme wind swing that reduces air clearance in the line. Even though the clearance requirement in this case is much lower than the case with transient overvoltage; the envelope here is highly elongated as shown in Figure 3.3 to account for extreme wind swing angle. In addition, the ideal clearance envelope under power frequency is also determined by the insulator string geometry and its contamination level.

3.5 Standard Recommendations for Electrical Clearance Distance Based on BSEN 50341 and BSEN 50423

This section addresses methods for calculating electrical clearance distances for overvoltages under lightning, switching and power frequency. The method described here is based on BSEN 50341-1 [3.5] for voltages greater than 45kV and BSEN 50423 [3.7] for distribution system voltages up to 45kV. BSEN 50341-1 uses the same method proposed by Central Research Institute of Electric Power Industry (CRIEPI) [3.12].

3.5.1 Approach for Lightning Overvoltages Calculation

The UHV-AC transmission committee of CRIEPI has proposed Equation (3.7) to calculate the approximate breakdown strength in air under positive polarity standard lightning impulses (1.2/50) applicable to rod-plane gap distance (d) up to 10 metres.

$$U_{50\%rp\_ff} = 530\ .\ d \tag{3.7}$$

Where, $U_{50\%rp\_ff}$ is the 50% withstand voltage of a rod-plane gap for fast front overvoltages in kV and d is the gap distance in metre.

This equation does not account for the statistical scatter of data, the actual overhead line gap geometry or geographical conditions. In order to account for these parameters, factors such as the statistical deviation factor (K_{z_ff}), the gap factor (K_{g_ff}) and the altitude correction factor (K_a) are introduced. Values of these factors are given in BSEN 50341-1 [3.5]. For determination of electrical clearance under lightning, the overvoltage to be considered is assumed to create a surge that propagates beyond a few towers from the point of the lightning strike. According to BSEN 50341-1, the '90%' lightning impulse withstand voltage of the insulator strings ($U_{90\%\_ff\_is}$) installed on a line need to be considered for calculating phase-to-earth clearance. The required electrical clearance distance (D_{el}) of a phase-to-earth configuration for lightning overvoltage may then be calculated using Equation (3.8) [3.5].

$$D_{el} = \frac{U_{90\%\_ff\_is}}{530\ .\ K_a\ .\ K_{z\_ff}\ .\ K_{g\_ff}} \tag{3.8}$$

Similarly, for phase-to-phase clearance, the withstand voltage of the insulator strings according to BSEN 50341-1 is considered 20% more than that of phase-to-earth clearance. i.e. the withstand voltage in this case is taken as $1.2U_{90\%\_ff\_is}$. Therefore, for the phase-to-phase configuration, the required electrical clearance distance (D_{pp}) is calculated using Equation (3.9) [3.5]. Refer to the next section for calculated results.

$$D_{pp} = \frac{1.2\ U_{90\%\_ff\_is}}{530\ .\ K_a\ .\ K_{z\_ff}\ .\ K_{g\_ff}} \tag{3.9}$$

3.5.2 Approach for Switching Overvoltages Calculation

Compared to lightning overvoltage performance, for a given gap distance, the breakdown strength of self restoring insulation under switching overvoltage is low. It is well established that air clearances needed for switching impulse withstand levels are higher than those required for the same magnitude lightning impulse withstand level [3.2]. IEC 60071-2 uses a semi-empirical equation proposed by *Paris* (Equation (3.10)) [3.13] to calculate the air gap distance for 50% withstand voltage ($U_{50\%}$).

$$U_{50\%} = 500\ d^{0.6} \tag{3.10}$$

BSEN 50341-1 [3.5] uses a different equation, proposed by CRIEPI, to calculate the same clearance. Equation (3.11) expresses the 50% breakdown strength ($U_{50\%rp\_sf}$) under positive polarity switching impulse applicable to rod-plane gaps (d) of up to 25 m.

$$U_{50\%rp\_sf} = 1080\ ln(0.46\, d + 1) \tag{3.11}$$

A number of research studies [3.13 – 3.17] have produced experimental results of the breakdown strength of air gaps under different electrode configurations and gap distance (d) using switching overvoltages. In [3.18], different equations describing the breakdown voltage were compared and reasonably close agreement with the published experimental results was found. A simple linear equation is proposed here to describe the breakdown voltage in the range 2m to 7m as given in Equation (3.12) [3.18].

$$U_{50\%} = C_1.d + C_2 \tag{3.12}$$

Coefficients C_1 and C_2 were calculated to obtain a best curve fit with minimum least square error. For rod-plane gaps with positive polarity impulse shape, values of C_1 and C_2 are 173.9 and 422.1 respectively.

In Figure 3.4, Paris's equation (Equation (3.10)), CRIEPI equation (Equation (3.11)), and the proposed linear equation (Equation (3.12)) are compared. The figure shows that the breakdown strength predicted by the three equations are quite close to each other in the gap distance range 2m to 7m, which is sufficient for determining insulation requirements for 275kV and 400kV systems. Hence, use of any of the three equations in determining the required clearance for the system considered in this study is justified. CRIEPI equation is used to determine clearance values in this work.

Similarly to the case of lighting overvoltage, to account for the statistical nature of breakdown, the actual overhead line gap geometry and geographical conditions, a statistical deviation factor (K_{z_sf}), a gap factor (K_{g_sf}) and an altitude correction factor (K_a) are used. The applicable overvoltage in this case is the value having 2% probability of being exceeded, as denoted by $U_{2\%\_sf}$. The breakdown strength ($U_{50\%rp\_sf}$) in the CRIEPI equation is then obtained by multiplying $U_{e2\%\_sf}$ by the statistical coordination factor (K_{cs}) to account for the risk of failure [3.5]. The required electrical clearance

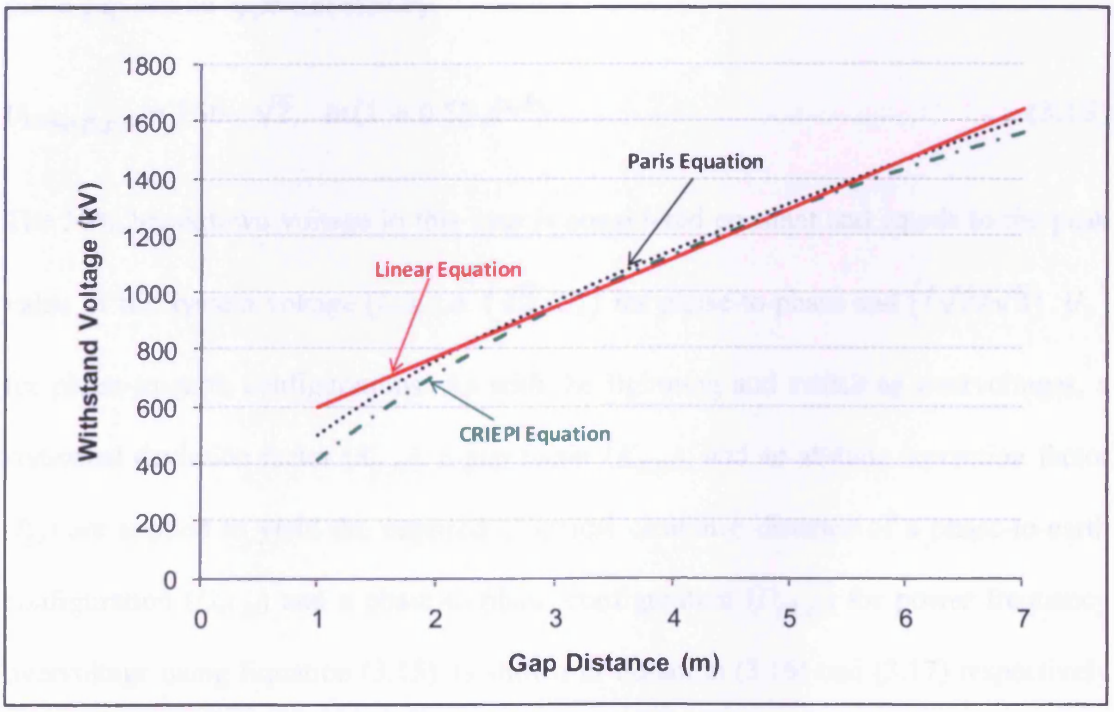


Figure 3.4: Comparison of switching impulse breakdown strength predicted by three different equations.

distance of a phase-to-earth configuration (D_{el}) for switching overvoltage is then derived using Equation (3.11) as shown in Equation (3.13) [3.5].

$$D_{el} = \frac{1}{0.46}\left(e^{\frac{K_{cs} \, . \, U_{e2\%\_sf}}{1080 \, . \, K_a \, . \, K_{z\_sf} \, . \, K_{g\_sf}}} - 1\right) \tag{3.13}$$

Similarly, for phase-to-phase clearance, the withstand voltage as per BSEN 50341-1 is considered 40% more than that of phase-to-earth configuration. i.e. the withstand voltage in this case is taken as $1.4U_{e2\%\_sf}$. Therefore, for the phase-to-phase configuration, the required electrical clearance distance (D_{pp}) is calculated using Equation 3.14 [3.5]. Refer to the next section for calculated results.

$$D_{pp} = \frac{1}{0.46}\left(e^{\frac{1.4 \, . \, K_{cs} \, . \, U_{e2\%\_sf}}{1080 \, . \, K_a \, . \, K_{z\_sf} \, . \, K_{g\_sf}}} - 1\right) \tag{3.14}$$

3.5.3 Approach for Power Frequency Overvoltages Calculation

For power frequency overvoltages, the 50% breakdown voltage ($U_{50\%rp\_pf}$) for a rod-plane gap can be approximated by:

$$U_{50\%rp\_pf} = 750 \, . \, \sqrt{2} \, . \, ln(1 + 0.55 \, d^{1.2}) \tag{3.15}$$

The 50% breakdown voltage in this case is considered constant and equals to the peak value of the system voltage (U_s). i.e. $\left(\sqrt{2} \, . \, U_s\right)$ for phase-to-phase and $\left(\left(\sqrt{2}/\sqrt{3}\right) . \, U_s\right)$ for phase-to-earth configurations. As with the lightning and switching overvoltages, a statistical deviation factor (K_{z_pf}), a gap factor (K_{g_pf}), and an altitude correction factor (K_a) are applied to yield the required electrical clearance distance of a phase-to-earth configuration (D_{el_pf}) and a phase-to-phase configuration (D_{pp_pf}) for power frequency overvoltage using Equation (3.15) as shown in Equation (3.16) and (3.17) respectively [3.5].

$$D_{el\_pf} = \left(\frac{e^{\frac{U_s}{750\,.\,\sqrt{3}\,.\,K_a .\,K_{z\_pf}\,.\,K_{g\_pf}}} - 1}{0.55} \right)^{0.83} \tag{3.16}$$

$$D_{pp\_pf} = \left(\frac{e^{\frac{U_s}{750\,.\,K_a .\,K_{z\_pf}\,.\,K_{g\_pf}}} - 1}{0.55} \right)^{0.83} \tag{3.17}$$

3.6 Appraisal of Electrical Clearance Distances Calculated Using CRIEPI Equations with IEC 60071 Specified Values

Using the CRIEPI equations from Section 3.5, electrical clearance distances are calculated for standard insulation levels specified in IEC 60071-1. The calculated clearances are compared with the published clearances given in IEC 60071-2 corresponding to all standard lightning and switching withstand levels for different system voltages.

IEC 60071-1 classifies the standard maximum r.m.s. value of system voltages (U_s) in to two ranges [3.1].

- Range I : 1kV < $U_s \leq$ 245kV (covers transmission and distribution systems)
- Range II : $U_s >$ 245kV (covers higher voltage transmission systems)

According to BSEN 50341-1, the electrical clearance distance in systems in Range I is mainly governed by overvoltage due to lightning and for the systems in Range II, it is governed by both lightning and switching overvoltages [3.5]. The clearance requirement for power frequency voltages is significantly less compared to the requirement for transient overvoltages. Therefore, the electrical clearances determined by transient overvoltages also cover the requirements due to power frequency voltage. The power-frequency withstand voltage for systems in Range I can be ignored when the ratio of the lightning impulse to the power frequency withstand voltage is greater than 1.7 [3.2].

Since, the systems considered in this study fall within the stated category, the calculations made here are based on the lightning and switching overvoltages only.

3.6.1 Calculation of Range I Voltages

In this range, clearance is mainly governed by lightning overvoltage. Therefore, the clearance requirements for five standard lightning impulse withstand voltage levels (60, 75, 95, 145 and 170kV) corresponding to maximum system voltage of 12kV and 36kV are calculated using Equations (3.8) and (3.9).

The following assumptions as recommended by BSEN 50341-1 have been made.

- up to the 200kV withstand level; a value of altitude correction factor, $K_a = 0.938$ is assumed for an altitude 1000m,
- the statistical deviation factor for lightning overvoltage, $K_{z\_ff} = 0.961$,
- the gap factor for lightning overvoltage, $K_{g\_ff} = (0.74 + 0.26\ K_g) = 1.117$ (for conductor-structure geometry considering $K_g = 1.45$) and $K_{g\_ff} = 1.156$ (for conductor-conductor geometry considering $K_g = 1.6$).

The calculated phase-to-earth clearance (using Equation (3.8)) and phase-to-phase clearance (using Equation (3.9)) for withstand voltage levels specified above are shown in Table 3.2. IEC 60071-1 specifies lightning impulse voltage level of 145kV and 170kV for a 36kV maximum system voltage. It can be seen from Table 3.2 that for lower value of withstand level (145kV), the minimum clearance of 0.27m and 0.31m respectively for phase-to-earth and phase-to-phase is required for uprating a line to a maximum system voltage of 36kV. Figure 3.5 compares the calculated phase-to-earth clearance values with corresponding clearances specified in IEC 60071-2. The calculated values appear to correspond quite closely with the IEC specified values. The maximum error of 18.2% is found at 60kV withstand voltage. At 145kV, error is 0%.

Table 3.2: Calculated electrical clearance values for IEC 60071-2 specified lightning impulse withstand levels corresponding to system voltages of 12kV and 36kV in Range I

Maximum System Voltage	12kV			36kV	
Lightning impulse withstand voltage	60kV	75kV	95kV	145kV	170kV
Phase-Earth clearance (m)	0.11	0.14	0.17	0.27	0.31
Phase-Phase clearance (m)	0.13	0.16	0.20	0.31	0.36

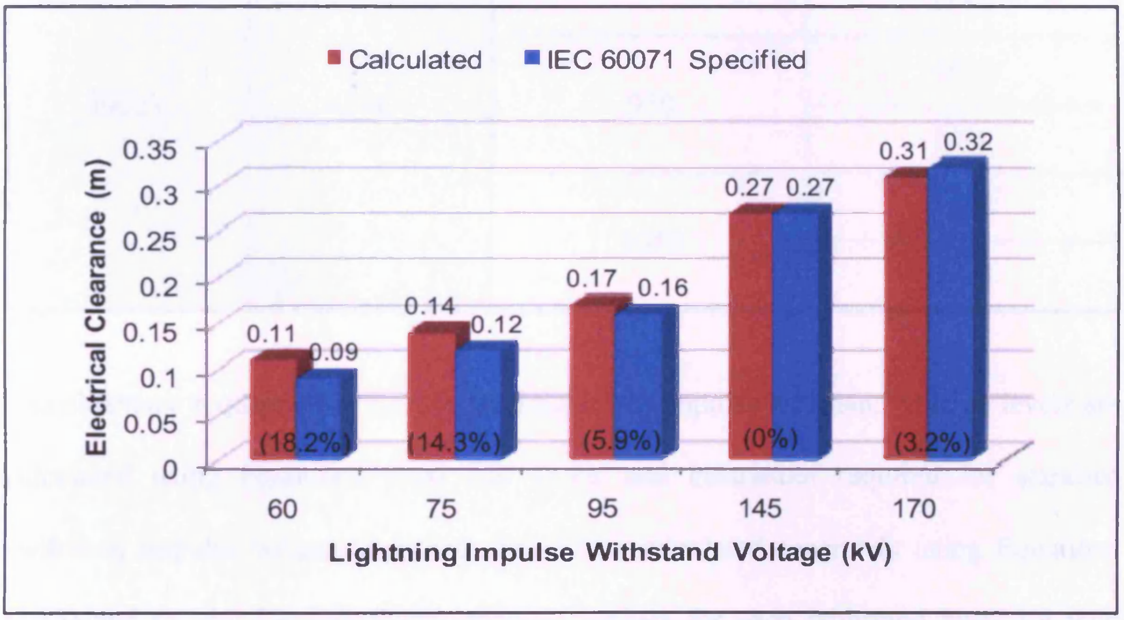


Figure 3.5: Comparison of calculated electrical clearance values (phase-to-earth) with clearance specified in IEC 60071-2 for specified lightning impulse level corresponding to system voltage of 12kV and 36kV in Range I. Values in parenthesis are percentage error.

3.6.2 Calculation of Range II Voltages

In this range, the calculations focus on a 275kV transmission line and its possible voltage uprating to 400kV. Clearance in Range II is governed by both the lightning and switching transient overvoltages. Therefore, calculations are done for all standard lightning and switching impulse withstand levels as shown in Table 3.3 for 275kV (U_s = 300kV) and 400kV (U_s = 420kV) system specified in IEC 60071-1.

Table 3.3: IEC 60071-1 specified standard lightning and switching impulse withstand levels for 275kV and 400kV system [3.1].

Nominal System Voltage ($kV_{r.m.s.}$)	Maximum System Voltage (U_s) ($kV_{r.m.s.}$)	Standard Impulse Withstand Level (kV_{peak})	
		Switching	Lightning
275kV	300kV	750	850
			950
		850	950
			1050
400kV	420kV	850	1050
			1175
		950	1175
			1300
		1050	1300
			1425

The clearance requirements for standard lightning impulse withstand voltage levels are calculated using Equations (3.8) and (3.9); and clearances required for standard switching impulse withstand voltage levels are calculated separately using Equations (3.13) and (3.14). The calculated clearance values for each withstand level are then compared with corresponding IEC specified clearances.

The assumptions made for calculating clearances in this study are as follows:

- values of altitude correction factor (K_a) for an altitude 1000m are:

  K_a = 0.970 (for withstand level between 701kV and 1100kV)

  K_a = 0.978 (for withstand level above 1100kV)

- the statistical deviation factor for lightning, K_{z_ff} = 0.961 and for switching, K_{z_sf} = 0.922,

- the gap factor for lightning overvoltage, K_{g_ff} = (0.74 + 0.26 K_g) = 1.117 (for conductor-structure geometry considering K_g = 1.45) and K_{g_ff} = 1.156 (for conductor-conductor geometry considering K_g = 1.6)
- the gap factor for switching overvoltage, K_{g_sf} = K_g = 1.45 (for conductor-structure geometry) and K_{g_sf} = K_g = 1.6 (for conductor-conductor geometry)

Table 3.4 shows the calculated clearance values for phase-to-earth and phase-to-phase clearances for different lightning impulse withstand levels, and Figure 3.6 shows a comparison of these clearances with IEC 60071-2 specified values. As can be seen in Figure 3.6a, the calculated phase-to-earth clearance value equals IEC specified value at 950, 1050, and 1425kV withstand voltage. The maximum error of 6.6% is found at 850kV. The calculated phase-to-phase clearance values as shown in Figure 3.6b is found to have maximum error of 4.5% at withstand voltage of 1050kV.

Table 3.4: Calculated electrical clearance values for IEC 60071-1 specified lightning impulse withstand levels corresponding to system voltage of 300kV and 420kV in Range II

Lightning impulse withstand voltage	850kV	950kV	1050kV	1175kV	1300kV	1425kV
Phase-Earth clearance (m)	1.5	1.7	1.9	2.1	2.3	2.6
Phase-Phase clearance (m)	1.7	1.9	2.2	2.4	2.7	2.9

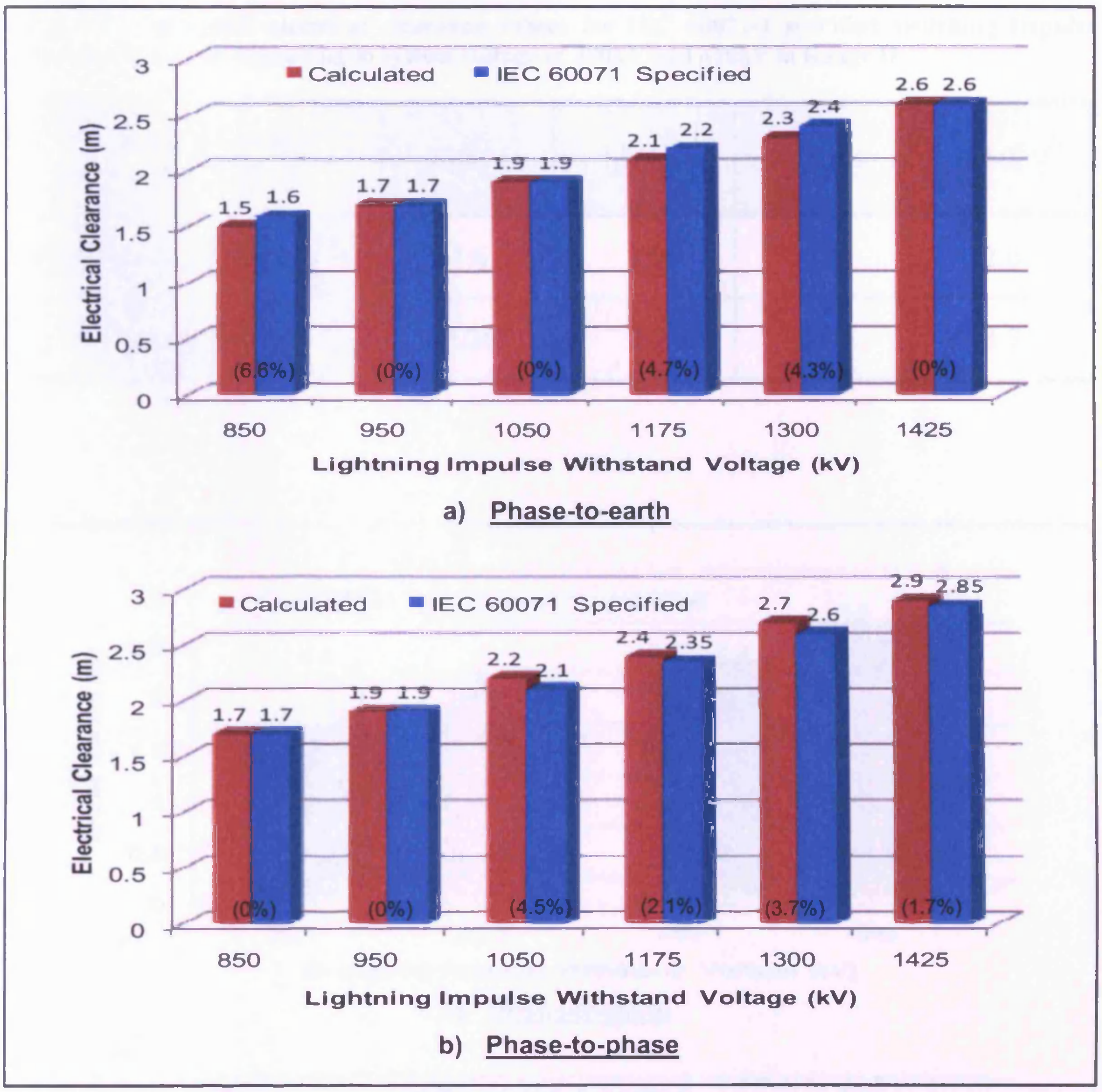


Figure 3.6: Comparison of calculated electrical clearance values with clearance specified in IEC 60071-2 for specific lightning impulse level corresponding to system voltages of 300kV and 420kV in Range II. Values in parenthesis are percentage error.

Similarly, Table 3.5 summarises calculated clearance values for phase-to-earth and phase-to-phase clearances for different switching impulse withstand levels, and Figure 3.7 compares these clearance values with IEC specified values. As can be seen in Figure 3.7a, the calculated phase-to-earth clearance value has 5.2% error at 850kV. At all other withstand level; the calculated values are same as that of IEC specified values. In case of phase-to-phase clearance (Figure 3.7b), the calculated values differ with IEC specified values with minimum error of 1.7% to maximum error of 3.7%.

Table 3.5: Calculated electrical clearance values for IEC 60071-1 specified switching impulse withstand levels corresponding to system voltage of 300kV and 420kV in Range II

Switching Impulse withstand voltage	750kV	850kV	950kV	1050kV
Phase-Earth clearance (m)	1.6	1.9	2.2	2.6
Phase-Phase clearance (m)	2.26	2.7	3.19	3.7

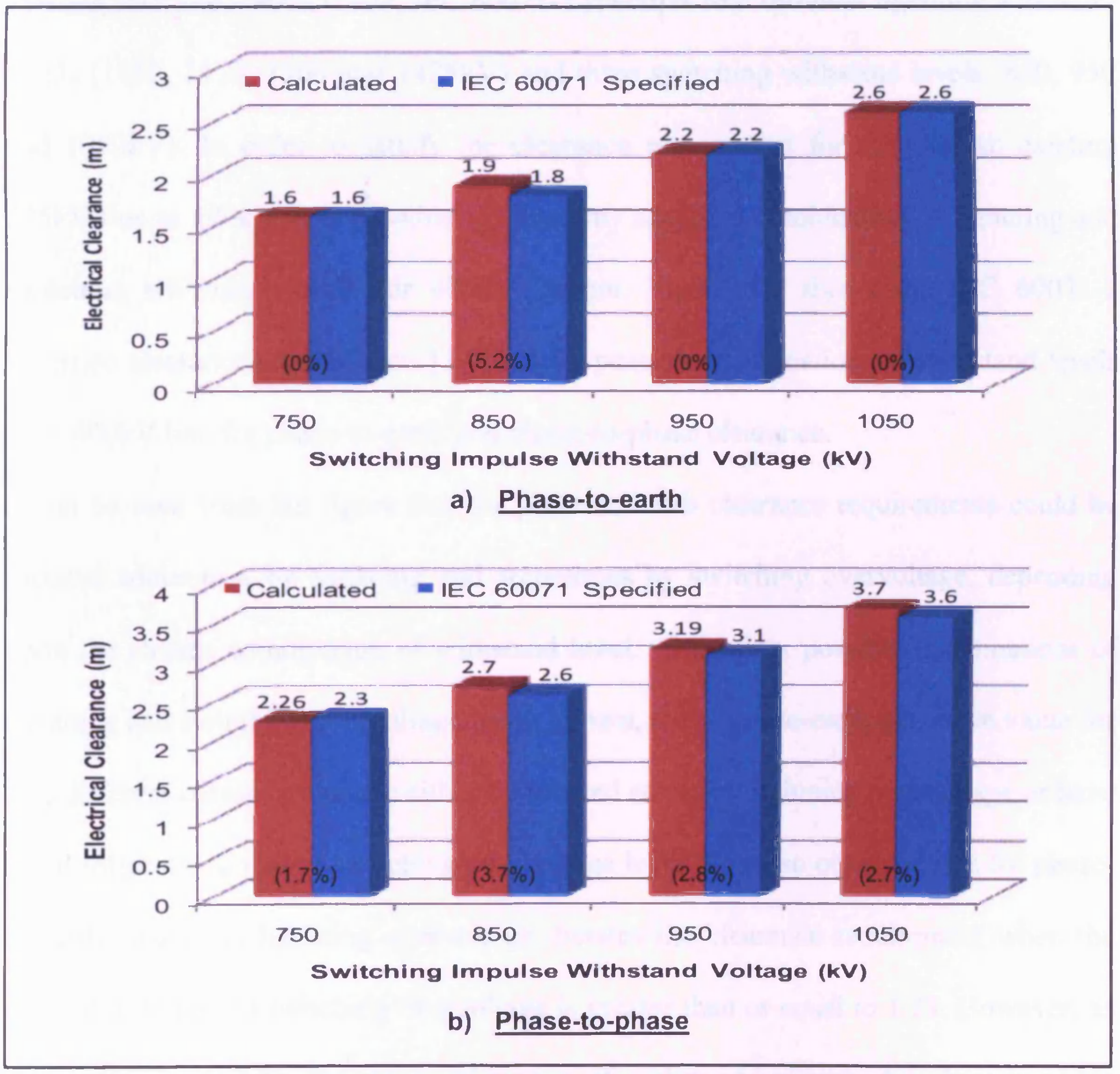


Figure 3.7: Comparison of calculated electrical clearance values with clearance specified in IEC 60071-2 for specified switching impulse level corresponding to system voltages of 300kV and 420kV in Range II. Values in parenthesis are percentage error.

The calculated values of clearances for lightning and switching overvoltages are important in voltage uprating process. These values satisfy the specifications commonly used by utilities in the United Kingdom. In the UK, withstand voltage levels of 1050kV / 850kV (lightning / switching) are adopted for 275kV line. A 400kV line adopts withstand level of 1425kV / 1050kV (lightning / switching). In order to uprate an existing 275kV line to 400kV, these withstand level increases require a considerable increase in electrical clearance values which may not be physically available in an existing line. For a 400kV line, IEC 60071-1 specifies four different lightning withstand levels (1050, 1175, 1300 and 1425kV) and three switching withstand levels (850, 950 and 1050kV). In order to satisfy the clearance requirement for uprating an existing 275kV line to 400kV, it is possible to adopt any specified combination of lightning and switching withstand levels for 400kV system. Figure 3.8 shows the IEC 60071-2 specified clearance requirements [3.2] for six possible combinations of withstand levels for a 400kV line for phase-to-earth and phase-to-phase clearance.

It can be seen from the figure that the phase-to-earth clearance requirements could be dictated sometimes by lightning and sometimes by switching overvoltage, depending upon the chosen combination of withstand level. Out of six possible combinations of lightning and switching overvoltage levels shown, the phase-to-earth clearance value for five different combinations are either dominated solely by lightning overvoltage or have equal influence to that of switching overvoltage level. It is also observed that for phase-to-earth clearance, lightning overvoltage dictates the clearance requirement when the ratio of lightning to switching overvoltage is greater than or equal to 1.23. However, as shown in Figure 3.8b, for any combination of withstand voltages, the phase-to-phase clearance requirement is solely dictated by the switching overvoltages. In this case, a switching overvoltage requires more clearance than the lightning overvoltage. Adopting different combinations of overvoltage level for a 400kV system could effectively reduce the clearance requirement for an uprated line. In order to consider which levels to adopt, it is necessary to examine available clearance in an existing system. Chapter 4 considers this issue in detail for a case of uprating an 'L3' type construction 275kV overhead transmission for uprating to 400kV.

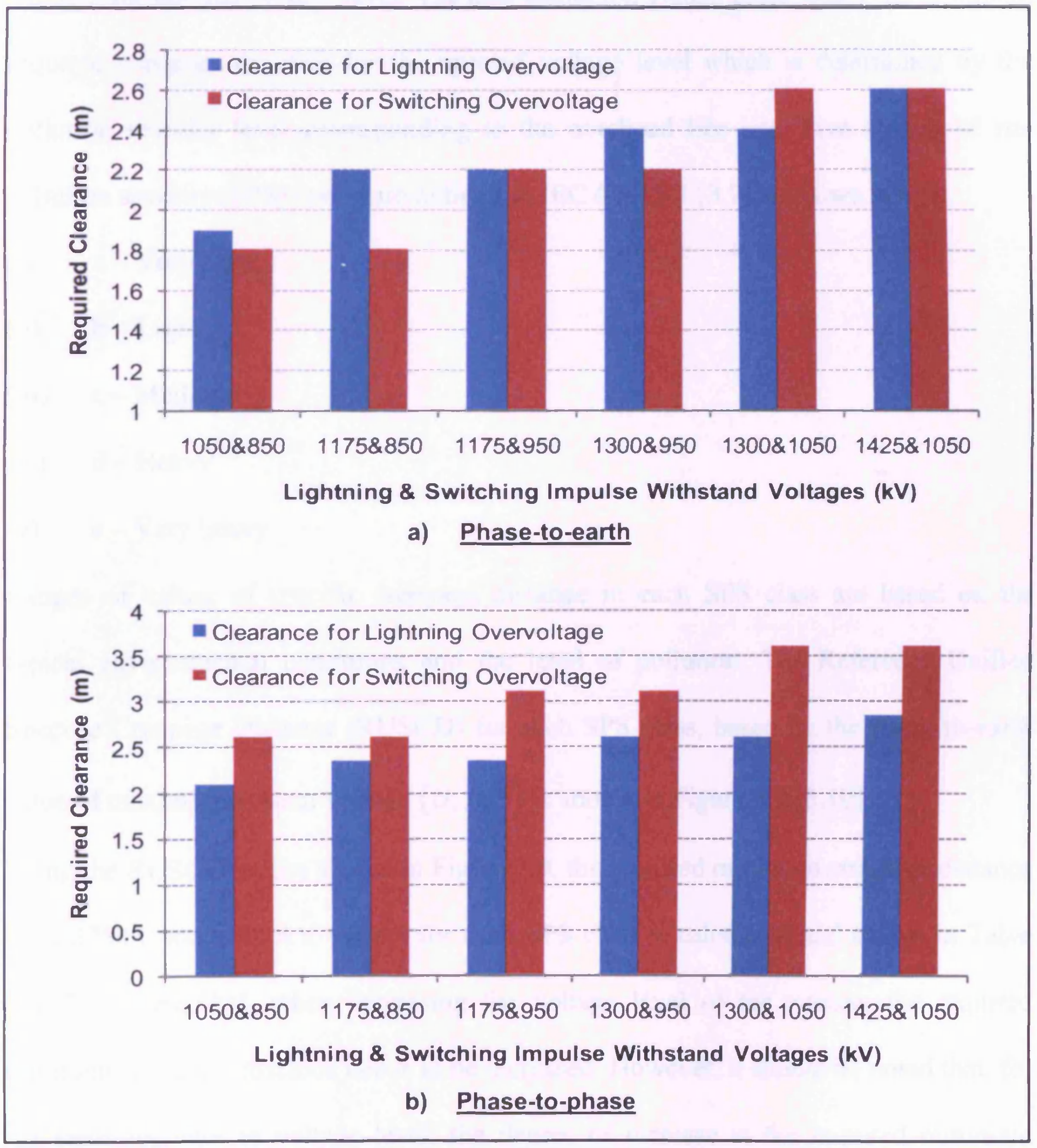


Figure 3.8: Clearance requirements for IEC 60071-2 specified combination of lighting and switching overvoltage levels for 420kV highest system voltage.

3.7 Insulation Electrical Strength Accounting for Pollution

In voltage uprating, apart from electrical clearance distance, the insulation electrical strength also plays significant role. Any increase in voltage level of an existing system demands increase in electrical strength of the existing insulation system. This may require insulator enhancement or the substitution of insulators to provide sufficient strength for uprated voltage level. The new insulation system must satisfy the minimum required creepage distance for the uprated voltage level which is determined by the pollution severity level corresponding to the overhead line site. Five classes of site pollution severity (SPS) levels are defined in IEC 60815-1 [3.9] as shown below:

(i) a – Very light

(ii) b – Light

(iii) c – Medium

(iv) d – Heavy

(v) e – Very heavy

Ranges of values of specific creepage distance in each SPS class are based on the typical environmental conditions and the level of pollution. The Reference Unified Specific Creepage Distance (RUSCD) for each SPS class, based on the phase-to-earth value of maximum system voltage $\left(U_s/\sqrt{3}\right)$ is shown in Figure 3.9 [3.10].

Using the RUSCD values shown in Figure 3.9, the required minimum creepage distance for a 275kV and a 400kV system for each SPS class is calculated and shown in Table 3.6. It is clear that, when increasing the voltage level of the system, the required minimum creepage distance needs to be increased. However, it should be noted that, for the same increase in voltage level, the degree of increase in the required minimum creepage distance varies according to SPS class. The relative increase in minimum creepage distance is greater moving from 'very light' to 'very heavy' SPS class.

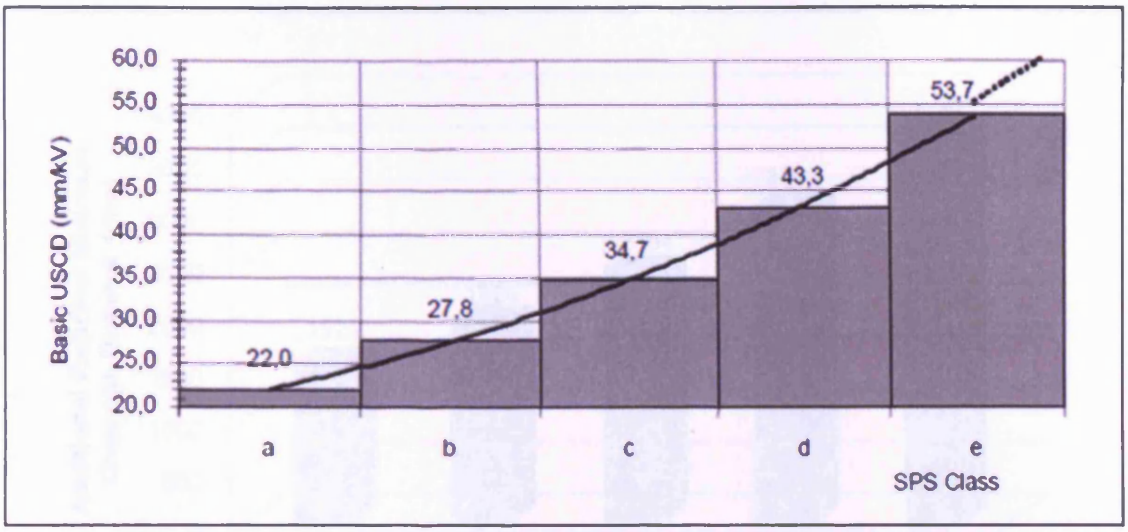


Figure 3.9: RUSCD as a function of SPS class [3.10].

Table 3.6: Calculated value of required minimum creepage distance for 275kV and 400kV line insulators under different pollution levels

SPS Class	RUSCD (mm/kV)	Minimum Required Creepage Distance (mm) $[RUSCD \times U_s/\sqrt{3}]$	
		275kV line (U_s = 300kV)	400kV line (U_s = 420kV)
a	22.0	3810	5335
b	27.8	4815	6741
c	34.7	6010	8414
d	43.3	7500	10500
e	53.7	9301	13021

This is graphically illustrated in Figure 3.10. As can be seen in the figure, for uprating the voltage level from 275kV to 400kV, the additional required minimum creepage distance varies from 1525mm in 'very light' SPS class to 3720mm in 'very heavy' SPS class. If a conventional cap and pin insulator string is used, the voltage uprating may require an increase in the insulator length by adding more discs. Figure 3.10 also shows the number of discs required to be added in an existing 275kV insulator string for

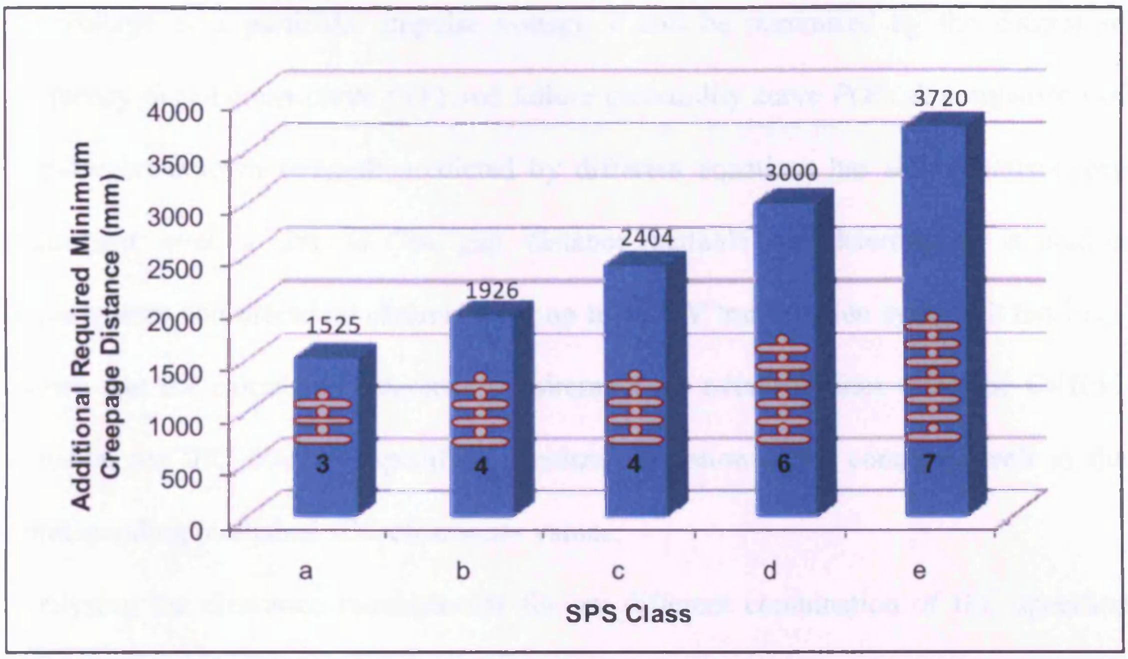


Figure 3.10: Additional required minimum creepage distance and number of glass insulator discs for increasing voltage from 275kV to 400kV under different pollution severity levels.

uprating it to 400kV system under different pollution levels. The numbers are calculated assuming glass insulator discs each having creepage distance of 540mm used in the 275kV system. However, adding more discs to an existing insulator string increases its length thereby reducing the phase-to-earth clearance of the line which would not be acceptable in the voltage uprating process as greater clearances are required.

Different techniques that provide high creepage within the same or shorter insulator lengths are required to be investigated to ensure insulation electrical strength for voltage uprating. Replacing existing insulators with composite insulators can provide high specific creepage ensuring air clearance in the line and could offer a solution to this problem. Chapter 4 considers such options for increasing creepage while uprating a 275kV overhead line to 400kV.

3.8 Conclusions

The insulation coordination process for voltage uprating was theoretically analysed for temporary and transient overvoltages. It was shown that the probability of occurrence of overvoltage at a particular impulse voltage V can be minimised by the control of frequency distribution curve $f(V)$ and failure probability curve $P(V)$. A comparison of impulse breakdown strength predicted by different equations has shown satisfactory agreement over a 2m to 7m gap distance suitable for determining insulation requirements and electrical clearance for up to 400kV transmission system. It has been shown that the calculated clearance requirement for overhead lines using the CRIEPI equation for IEC 60071-1 specified standard insulation levels compares well to the corresponding published IEC clearances values.

Analysing the clearance requirements for six different combination of IEC specified lightning and switching overvoltage levels for a 400kV system, it was found that the phase-to-earth clearance requirement for majority (5 out of 6) of the combinations are either dictated by lightning overvoltage or have equal influence to that of switching overvoltage. However, the phase-to-phase clearance requirement was found to be solely dictated by the switching overvoltages. The opportunity to select a particular combination of withstand voltages was identified to increase the possibility for uprating. It was shown that to satisfy insulation electrical strength while uprating a 275kV line to 400kV requires additional creepage ranging from 1525mm to 3720mm depending on the class of pollution levels of the transmission line environment. The simple concept of increasing electrical strength by increasing insulator length was discarded due to the consequent reduction in clearances which would further restrict options for uprating in terms of withstand voltage levels.

CHAPTER 4

ANALYSIS OF ELECTRICAL CLEARANCES

4.1 INTRODUCTION

A voltage uprating study necessitates identification of the new voltage level in which the existing line will uphold its reliability. To increase the power transfer capability of overhead lines by voltage uprating, different design criteria need to be addressed. These include technical, financial and environmental issues. In Chapter 3, one of the most important technical issues to be assessed in voltage uprating was found to be the electrical clearance, and this is a challenging task and is fundamental to ensure satisfactory performance for power frequency, lightning and switching overvoltages corresponding to the uprated voltage level.

In this chapter, an extensive analysis of the electrical clearance issues for voltage uprating of a transmission line is carried out. Initially, the available clearances of the existing line are thoroughly examined so that any insufficiencies in the clearances for higher voltage level are identified. Then, techniques are explored for satisfying the clearances requirements with uprating the line. The electrical clearance aspects of voltage uprating are investigated based on an operational 275kV transmission line with a standard 'L3' tower structure which is selected for possible voltage uprating to 400kV. Issues such as conductor air clearance and insulation electrical strength are taken into account to identify an appropriate methodology for uprating the line to 400kV.

4.2 DETAILS OF THE SELECTED 275KV OVERHEAD LINE

The line under consideration for uprating is a 35km long, double circuit 275kV line of 'L3' steel construction. For this type of construction, the height of the steel lattice tower is 36.88m [4.1]. The line is assumed to be located on flat terrain with an average span length of 300m. Figure 4.1 shows a section of a typical 275kV line in 'L3' tower structure.

The phase conductors of the line comprise twin 175mm^2 ACSR (Aluminium Conductor Steel Reinforced) 'Lynx' conductor, and a single 'Lynx' conductor is used for the earth wire. Some of the existing 275kV lines in the UK have had the ACSR conductors replaced with 'Upas' AAAC (All Aluminium Alloy Conductors) to increase power transfer capability of the line [4.2, 4.3]. However, most of the 275kV lines were designed and constructed in the 1950s and 1960s to accommodate ACSR 'Lynx' conductors. Therefore, the 'Lynx' conductor is selected in this study to represent the scenario of the existing system for which the line was initially designed [4.4]. With 'Lynx' conductors, the phase and earth conductors have a 7.05m and 6.66m mid-span sag respectively under normal weather (no wind and ice loading with average surrounding temperature of 5 °C) conditions [4.1].

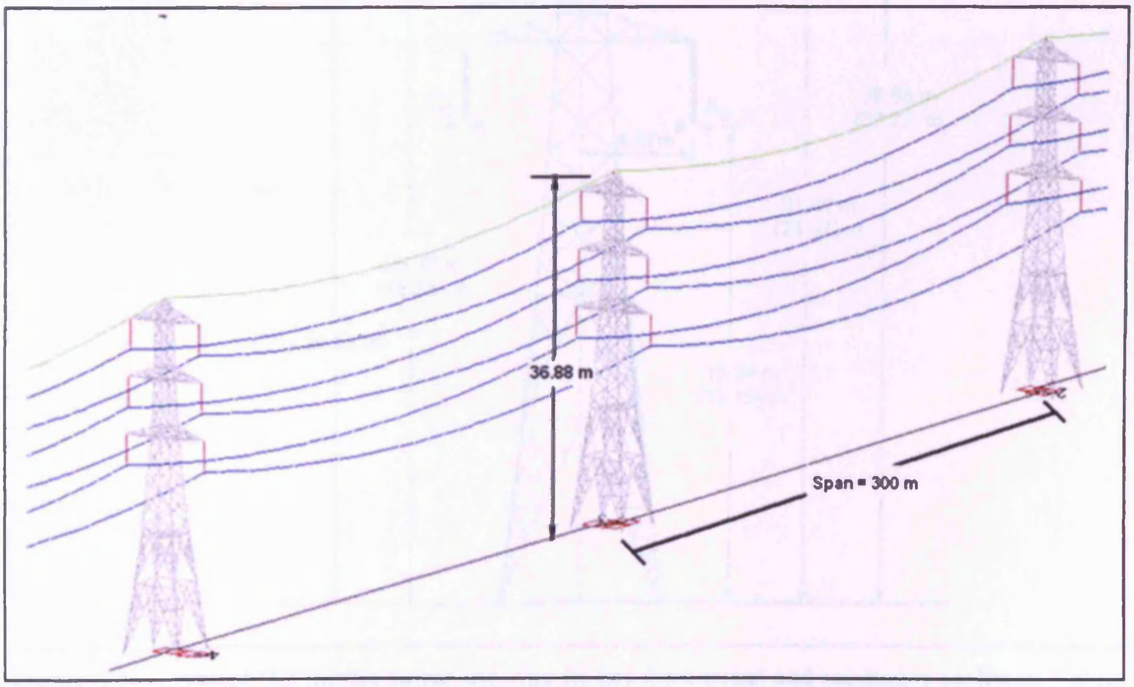


Figure 4.1: Section of a 275kV overhead transmission line in 'L3' tower structures.

4.2.1 Tower Structure and Conductor Geometry

A typical 'L3' type standard suspension tower can support loading tension up to 72kN. Each crossarm of the tower can support maximum weight of 30kN. Figure 4.2 shows the structure of such an 'L3' tower labelled with coordinates of the conductors [4.1]. The values in the parentheses are midspan heights of conductors. Conductors A_1, B_1, C_1 on left are phase conductors of the first circuit and A_2, B_2, C_2 on right correspond to the second circuit with the phasing arrangements as shown in the figure. The shielding angle of the earth wire is 34.5^0.

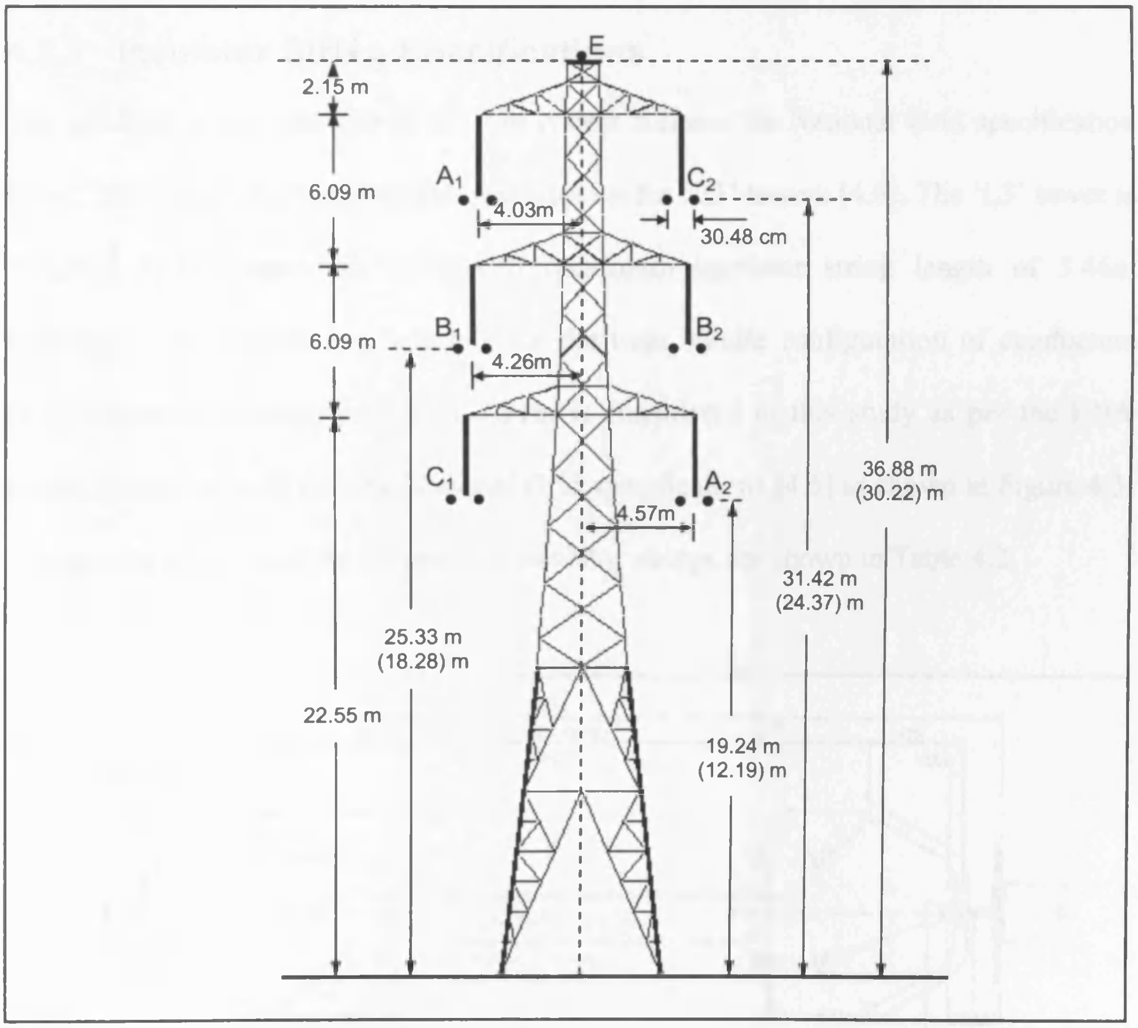


Figure 4.2: A typical 'L3' lattice tower showing its key dimensions and conductor positions. Values in parentheses show the midspan height of conductors.

4.2.2 Conductor Specifications

The specifications for the conductors are shown in Table 4.1 [4.1, 4.4, 4.5].

Table 4.1: Specifications for the phase and earth conductors [4.1, 4.4, 4.5].

Parameters	Description
Conductor	Lynx (ACSR)
Cross-sectional area	175mm^2
Diameter	19.53mm
Number of sub-conductors in a bundle	2 (for phase) and 1 (for earth)
Bundle spacing	30.48cm
Breaking load	79.80kN

4.2.3 Insulator String Specifications

The insulator string considered for this system follows the National Grid specification for a 275kV overhead transmission insulator set for 'L3' towers [4.6]. The 'L3' tower is designed to accommodate an overall maximum insulator string length of 3.46m including a steel attachment suitable for the twin bundle configuration of conductors [4.7]. However, a string length of 3.31m is considered in this study as per the ENA recommendation [4.8] and the National Grid specifications [4.6] as shown in Figure 4.3. The specifications used for suspension insulator strings are shown in Table 4.2.

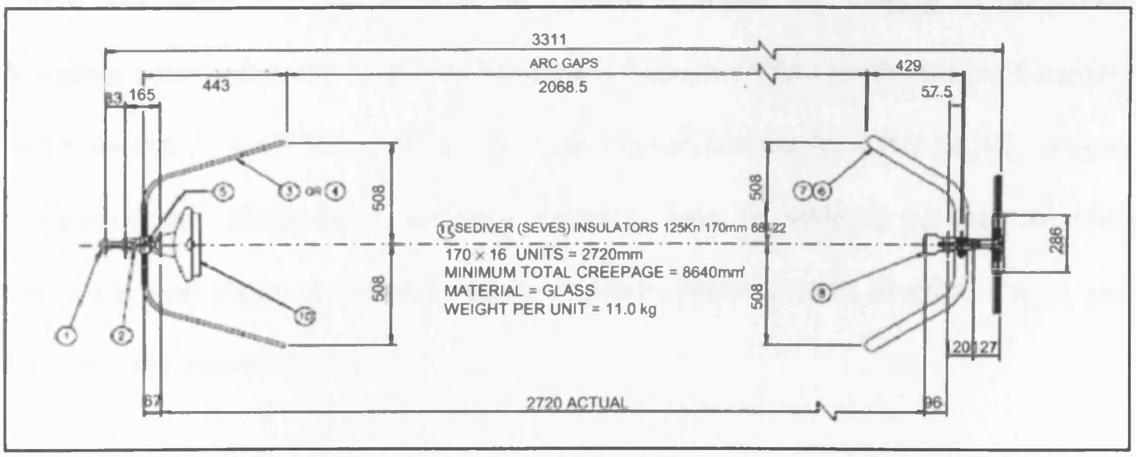


Figure 4.3: 275kV suspension insulator set for 'L3' towers (Reconstructed from [4.6])

Table 4.2: Specifications for suspension insulators

Parameters	Description
Disc material	Glass
Number of discs in a string	16
Nominal spacing	170mm (each disc)
Minimum creepage	540mm (each disc)
Minimum total creepage	8640mm
String insulator length	3311mm
Minimum failing load	125kN
Total Weight of the string	206kg

4.3 Analysis of Conductor Air Clearances

The available conductor air clearances in the 'L3' 275kV overhead line are examined for different loading cases as specified in BSEN 50341-1 [4.9]:

- Still air (with maximum conductor temperature or ice load)
- Wind load

These conditions are considered as the general approach for loading in the United Kingdom specified in the "National Normative Aspects (NNA) for the United Kingdom and Northern Ireland" for overhead electrical lines exceeding AC 45kV [4.10]. In order to increase the voltage level, sufficient clearance must be achieved between the mid-span of lowest phase and ground, phase-to-phase, phase-to-earth structure / wire, and for live line maintenance [4.11].

4.3.1 Clearances under Still Air (Normal Load / Maximum Conductor Temperature / Ice Load)

Conductor air clearance in still air is calculated for the 'L3' 275kV system operating under three different loads:

(i) normal load,

(ii) maximum load and maximum conductor temperature, and

(iii) ice loading.

In all the cases, under still air condition, the required minimum clearance is determined by D_{el} (for phase-to-earth clearance) and D_{pp} (for phase-to-phase clearance) as defined in Section 3.5 of this thesis. The standard conditions specified in the NNA [4.10] are adopted for the different loading conditions in still air (wind speed less than 0.6m/s) and is described in Table 4.3:

Table 4.3: NNA specified still air loading condition [4.10].

Parameters	Description
Nominal altitude loading	1000m
Average surrounding temperature	5 °C
Conductor temperature for normal load	50 °C
Air temperature for maximum load	20 °C
Wind speed	0.6 m/s perpendicular to tower and conductor (Normal to all)
Radial ice thickness	55mm
Ice density	5 kN/m^3 at -10 °C for ice load
Insulator swing	0^0

The 'L3' 275kV line considered in this study operates with lightning and switching impulse withstand voltage level of 1050kV and 850kV respectively. Similarly, for a 400kV system, withstand voltage level of 1425kV / 1050kV (lightning / switching) is generally used in the UK. Therefore, the minimum required clearances for 275kV and 400kV systems for the above mentioned withstand voltage levels are calculated using Equations (3.8) and (3.9) for lightning overvoltage; Equations (3.13) and (3.14) for switching overvoltage and; Equations (3.16) and (3.17) for power frequency voltage (see Chapter 3 for further details of above equations). The calculated values that are applicable to clearances at towers and within the spans are shown in Table 4.4. It can be seen that there is a significant increase in clearances when uprating the line from 275kV to 400kV system.

Table 4.4: Calculated values of minimum required clearances (in meter) under still air condition for 275kV and 400kV overhead line.

Clearance Type	275kV OH Line			400kV OH Line		
	Power Frequency	Switching Impulse	Lightning Impulse	Power Frequency	Switching Impulse	Lightning Impulse
	300kV	850kV	1050kV	420kV	1050kV	1425kV
Phase-to-Earth (D_{el})	0.51	1.9	1.9	0.69	2.6	2.6
Phase-to-Phase (D_{pp})	0.83	2.7	2.2	1.16	3.7	2.9
Ground	7.0*			7.3*		

* The value is according to the NNA specification for UK and Northern Ireland [4.10].

The phase-to-phase and phase-to-earth clearances available for the existing 275kV line are shown in Figure 4.4. The ground clearances at the tower attachment points and at midspan are shown in Figure 4.2. As expected, the design of the 275kV line satisfies all clearance requirements between conductors and conductor-earth to prevent flashover

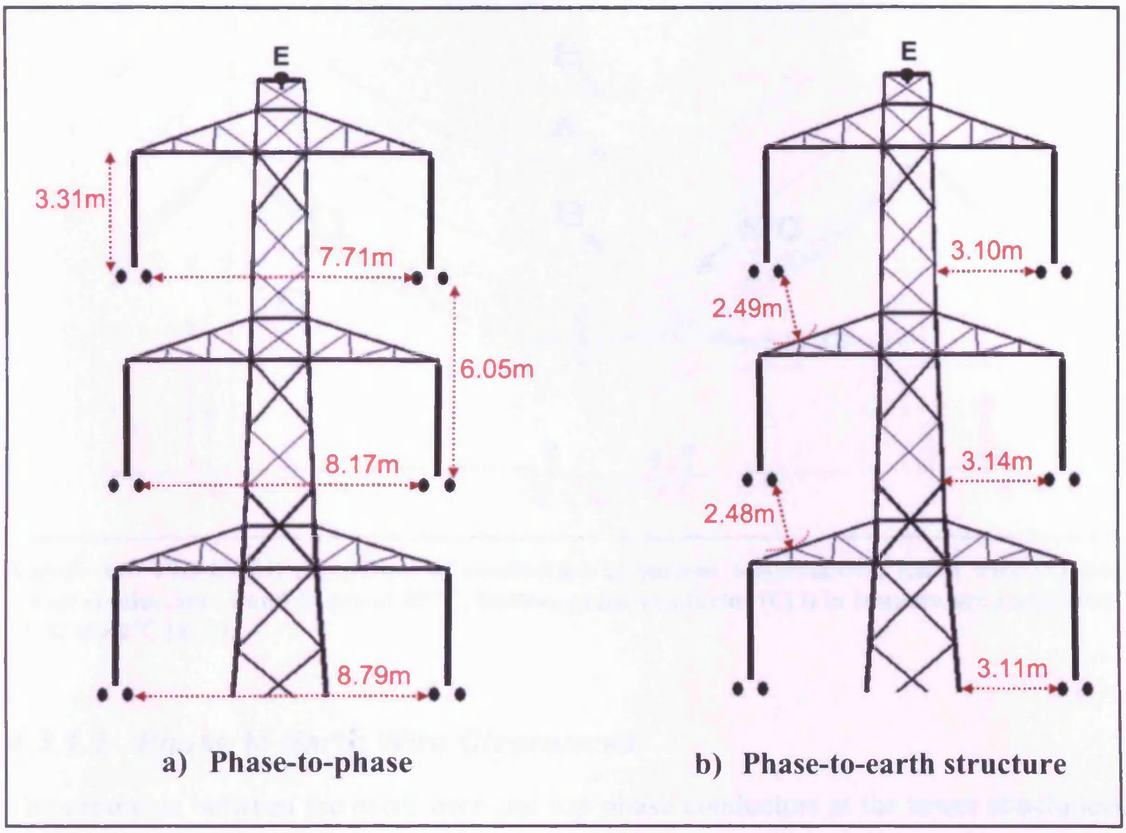


Figure 4.4: Available air clearances between critical points for standard 'L3' 275kV line with normal suspension in still air.

due to all types of overvoltages. The available clearances are exceeding the minimum required clearances for operation at 275kV system. If the line is uprated to 400kV, satisfactory clearance should be achieved between phase and ground, phase to phase, phase to earth wire and, phase to tower structure.

4.3.1.1 Phase to Ground Clearances

The available minimum phase-to-ground clearance within the span is 12.19m for the lowest two phase conductors (Figure 4.2). This value is significantly greater than the required ground clearance for the 400kV system by 4.89m under normal loading condition. The excess of 4.89m clearance provides sufficient room for further sag due to increase in temperature up to maximum thermal loading conditions. A parallel research within the project on the same line has shown no violation of ground clearance for bottom conductors up to thermal loading of 90 °C as shown in Figure 4.5 [4.12].

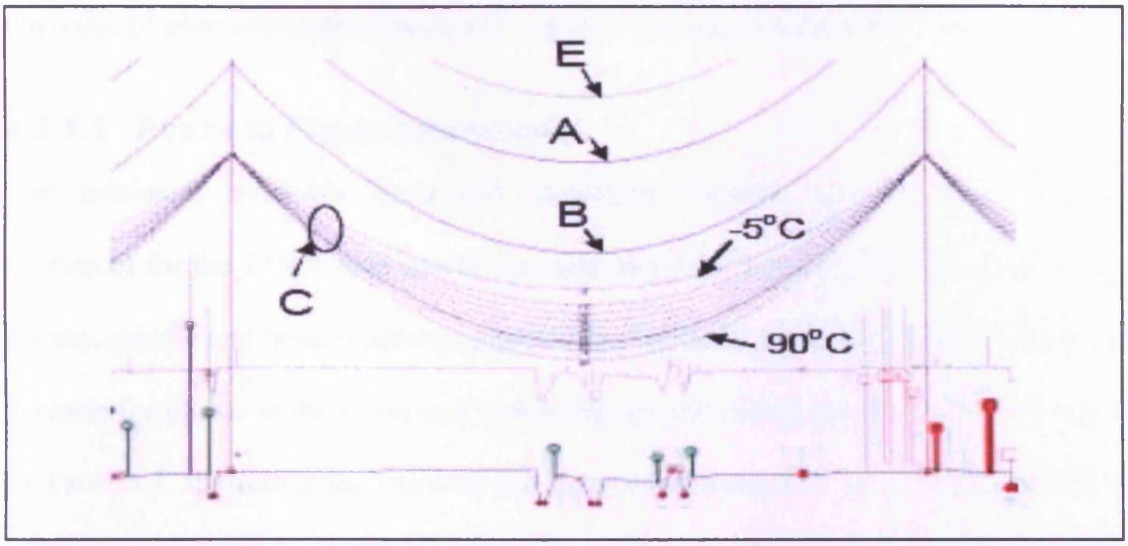


Figure 4.5: PLS-CADD simulation of conductors at various temperatures. Earth wire (*E*) and phase conductors (*A* and *B*) are at 65 °C. Bottom phase conductor (*C*) is in temperature range from -5 °C to 90 °C [4.12].

4.3.1.2 Phase to Earth Wire Clearances

The clearance between the earth wire and top phase conductors at the tower attachment position and at midspan, are shown in Figure 4.6. The values of clearance are 6.66m at the tower attachment position and 6.98m at midspan which are significantly higher than

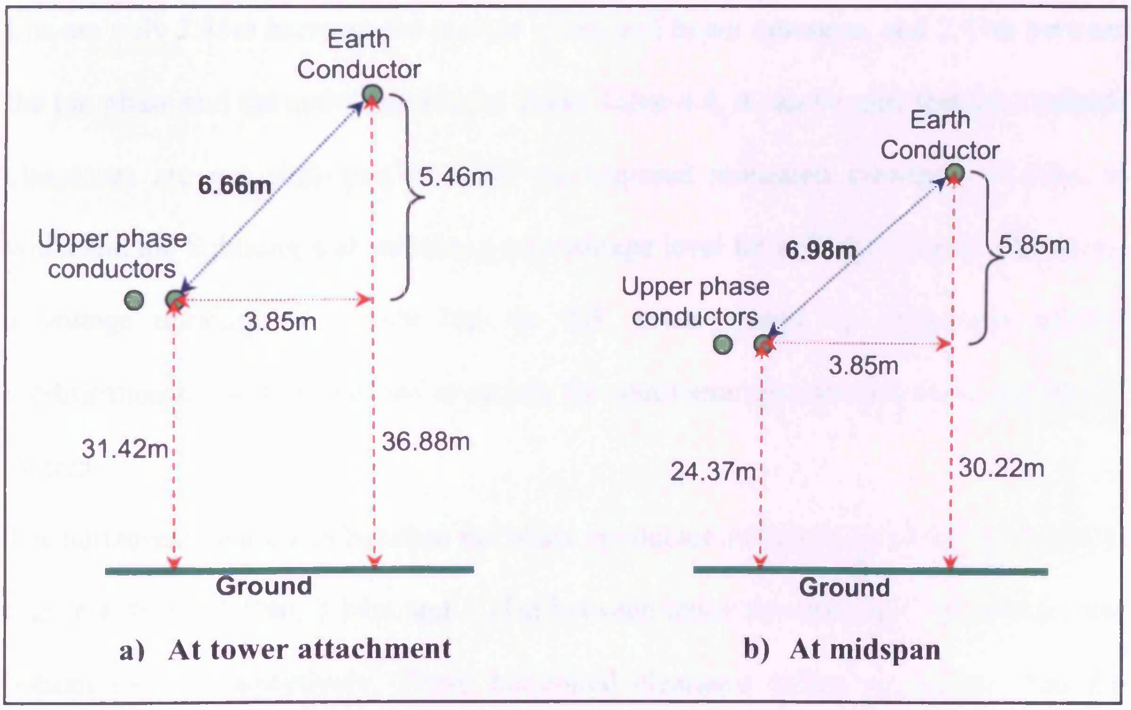


Figure 4.6: Clearances between the top phase conductors and earth wire at a) tower attachment point and b) midspan.

the required phase-to-earth clearance (2.6m for switching) for the 400kV system.

4.3.1.3 Phase to Phase Clearances

The minimum available horizontal clearances between phases (phase-to-phase clearance) for the 275kV line in still air condition are 7.71m, 8.17m and 8.79m across the top, middle and bottom phases respectively. Similarly, minimum vertical clearances between the phases at the tower and within the span are 6.05m (Figure 4.4 a). As shown in Table 4.4, the minimum required phase-to-phase clearances are 2.7m for a 275kV system and 3.7m for a 400kV system. The available phase-to-phase clearance in an existing 275kV line in still air condition shows that there are adequate air clearances between the phases for uprating to a 400kV system. The clearances are almost double the most onerous required clearance of 3.7m needed to withstand switching impulse voltage for 400kV operation.

4.3.1.4 Phase to Tower Structure (Phase to Earth) Clearances

As seen in Figure 4.4 b, the minimum available phase-to-earth clearances for the 275kV line are only 2.48m between the middle phase and lower crossarm, and 2.49m between the top phase and the middle crossarm. From Table 4.4, it can be seen that the available clearances are not sufficient to fulfil the required minimum clearance of 2.6m to withstand the lightning and switching overvoltage level for a 400kV system. Therefore, a voltage uprating of 275kV line in 'L3' tower would be impossible without modification to the existing line to satisfy the minimum required clearances for 400kV system.

The horizontal clearances between the phase conductor and tower structure, as shown in Figure 4.4b are 3.10m, 3.14m and 3.11m between tower structure and top, middle, and bottom phases respectively. These horizontal clearance values are higher than the required minimum phase-to-earth clearance (2.6m) for 400kV system. However, these phase-to-earth clearances (between phase and tower structure) are for a still air condition where there is no swing in the insulator string. The effect of swing angle on clearances is considered next.

4.3.2 Clearances under Wind Loading

The following two conditions are considered as per BSEN 50341-1 [4.9] recommendation to assess conductor air clearance under wind load.

- Wind load for 3 years return period : Design wind load for determination of electrical clearances (Normal wind)
- Wind load with 50 years return period : Wind load for gust conditions (Extreme wind)

In case of normal wind load, similar to that of still air condition, the minimum required air clearances are mainly governed by lightning and switching overvoltages. However, the required clearances under this case may be less than that of the still air condition due to the low probability of overvoltage causing any risk of failure [4.9]. Therefore, the phase-to-earth and phase-to-phase clearances required for lightning and switching overvoltage under normal wind load is obtained by reducing corresponding required clearances (D_{el} and D_{pp}) under still air by a factor k_1, known as the reduction factor for electrical clearances, [4.10].

The ideal geometry of the clearance envelopes for different overvoltages described in Section 3.4 indicated that insulator swing due to wind load has a significant effect on flashover under power frequency overvoltage. Under extreme wind, it is less likely to have a transient overvoltages occurring simultaneously when the conductor swings due to wind load and the clearances should only withstand the highest system voltage (power frequency) [4.9]. Therefore, the phase-to-earth and phase-to-phase clearance requirement in this case is governed mainly by the power frequency overvoltage and the values are the same as those of still air condition represented by D_{el_pf} and D_{pp_pf} (Equation (3.16) and (3.17)).

Table 4.5 shows the calculated values of minimum required clearances for 275kV and 400kV operation under normal and extreme wind conditions. For normal wind, the calculated D_{el} and D_{pp} values shown in Table 4.4 are multiplied by clearance reduction factor $k_1 = 0.7$ as recommended by NNA for the UK and Northern Ireland.

Table 4.5: Calculated values of minimum required clearances (in meter) under wind load (normal wind & extreme wind) for 275kV and 400kV overhead line under different overvoltages

	Clearances	275kV OH Line		400kV OH Line	
Normal Wind		Switching Impulse 850kV	Lightning Impulse 1050kV	Switching Impulse 1050kV	Lightning Impulse 1425kV
	Phase-to-earth ($k_1 \times D_{el}$)	1.33	1.33	1.82	1.82
	Phase-to-phase ($k_1 \times D_{pp}$)	1.89	1.54	2.59	2.03
Extreme Wind		Power Frequency 300kV		Power Frequency 420kV	
	Phase-to-earth (D_{el_pf})	0.51		0.69	
	Phase-to-phase (D_{pp_pf})	0.83		1.16	

Figure 4.7 shows the conductor air clearances during normal swing (under normal wind, shown on the left hand circuit) and extreme swing (under extreme wind, shown on right hand circuit). The normal swing angle assumed to be 20^0 and the extreme swing angle is 35^0. (The 'L3' tower was initially designed for 30^0 swing angle).

The minimum available phase-to-earth (phase-to-crossarm) clearances during normal

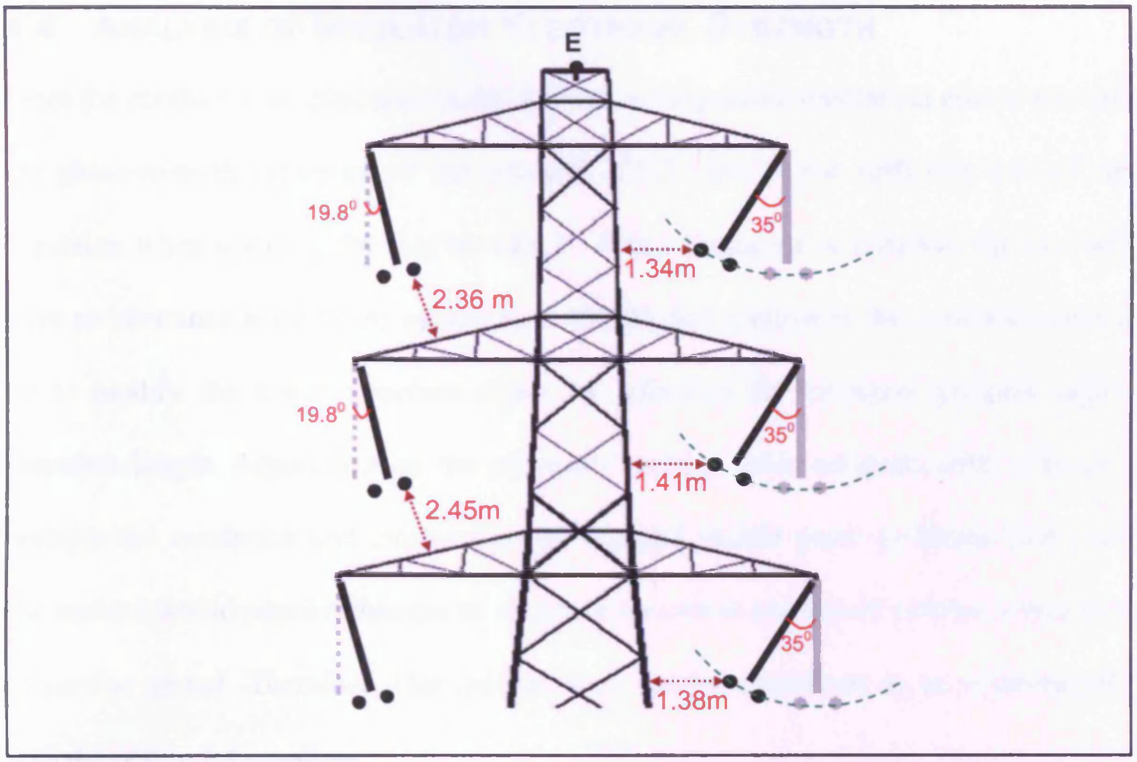


Figure 4.7: Available air clearance for standard 'L3' 275kV line with normal suspension in wind load. Left hand side phases under normal swing and right hand side phases under extreme swing.

wind load are 2.36m and 2.45m for the top and middle phase conductors respectively. Compared to the still air condition (shown in Figure 4.4), these clearances decrease by 0.13m for the top phase and 0.03m in the bottom phase. The reduction in the clearance is due to the insulator swing and the minimum clearances occur at 19.8^0 swing angle. Comparing these reduced clearances due to normal swing (2.36m and 2.45m) with the required minimum clearances shown in Table 4.5, it is seen that the available phase-to-crossarm clearances in both the phases of the existing 275kV line satisfies the required minimum clearances of 1.82m for 400kV system.

Under extreme wind load, (35^0 swing angle) the available clearances in all phases exceed 1.3m. With reference to the required minimum values under extreme wind as shown in Table 4.5, it can be seen that the available clearances are sufficient to operate at 400kV.

4.4 ANALYSIS OF INSULATOR ELECTRICAL STRENGTH

From the conductor air clearance point of view, an important conclusion drawn was that the phase-to-earth clearance of the existing 275kV line is not sufficient for still air condition when uprating the line to 400kV. If this clearance is satisfied, the line will have no clearance issue for its operation at 400kV.One solution to this restriction would be to modify the tower structure either by adjusting the crossarm position and/or crossarm length. Adjustment to the crossarm could provide adequate earth clearance between the conductor and crossarm at the top and middle phase positions. However, the method would require changes to all tower structures and would involve a long out-of-service period. Therefore, this method may not be considered as an economically realistic option for uprating.

Another solution to achieve adequate phase-to-earth clearance could be achieved by adjusting the insulator axial length and its creepage. The required phase-to-earth clearance of 2.6m for 400kV operation under still air can be obtained by reducing the length of insulator string from its current length of 3.31m to 3.2m. Figure 4.8 shows the proposed phase-to-earth clearance with a 3.2m insulator string.

Increasing the voltage rating of the line adds to the creepage requirement of an existing insulator. Therefore, reduction of the insulator length is only possible if the reduced insulator length can provide a higher creepage value required for the uprated voltage level. This could probably be achieved by replacing the existing glass insulators by alternative polymeric insulators that can provide higher value of unified specific creepage distance (USCD). In order to investigate this solution, it is necessary to estimate the additional creepage required for the increased voltage level which is determined by the overhead line site pollution severity level (SPS).

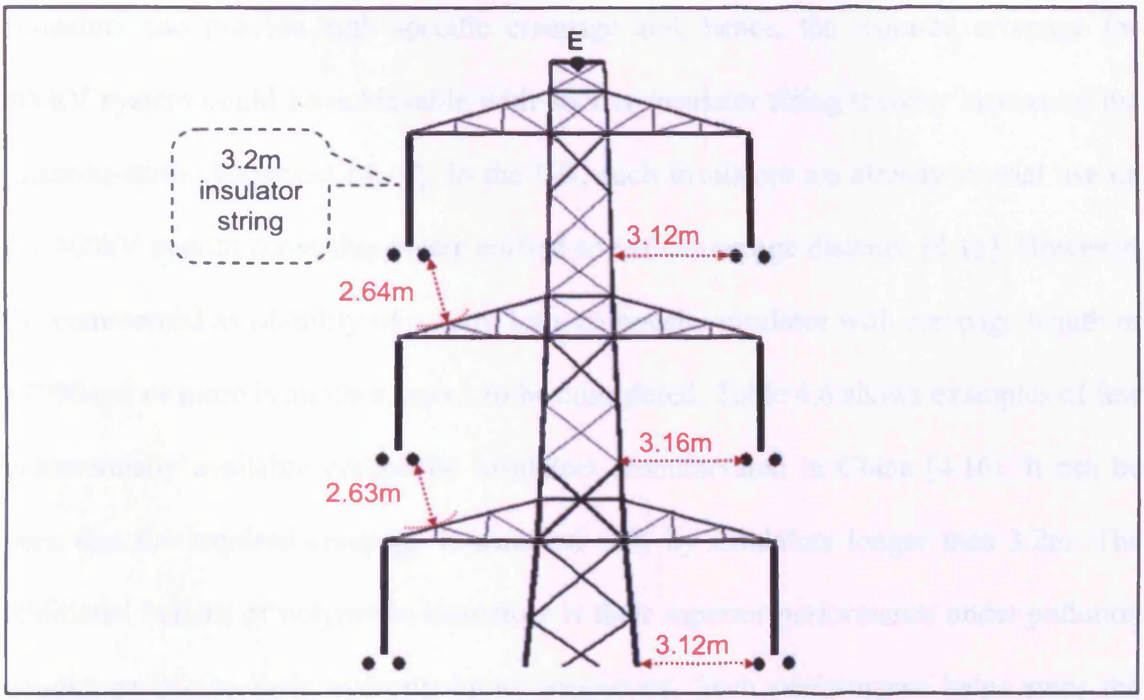


Figure 4.8: Phase-to-earth clearances obtained with 3.2m insulator string.

4.4.1 Estimation of Additional Creepage for Uprated 400kV System

The existing 275kV glass insulator string has a total creepage of 8640 mm [4.6]. This gives a minimum unified specific creepage distance of 49.883 mm/kV between phase and earth related to the phase-to-earth highest system voltage $(U_s/\sqrt{3})$ for a system voltage of 275kV according to IEC 60815-1 [4.13]. This value, according to Figure 3.9 in Chapter 3, is adequate for a site pollution severity (SPS) between 'Heavy' and 'Very heavy' levels that require average values of USCD of 43.3 mm/kV and 53.7 mm/kV respectively. To maintain the same SPS class and the same corresponding USCD, the insulators of the uprated line at 400kV system would require a minimum creepage of $49.883 \times \frac{420}{\sqrt{3}} = 12096$ mm. Therefore, to obtain 2.6m phase-to-earth clearance, a 3.2m insulator string with a minimum creepage of 12096 mm is required. In other words, a shorter insulator with high creepage distance is necessary. The application of a composite polymer insulator could provide the solution. Light weight polymer insulators can provide high specific creepage and, hence, the required creepage for 400kV system could be achievable with shorter insulator string thereby increasing the phase-to-earth clearances [4.14]. In the UK, such insulators are already in trial use on the 400kV system providing better unified specific creepage distance [4.15]. However, the commercial availability of a 3.2m long composite insulator with creepage length of 12096mm or more is another aspect to be considered. Table 4.6 shows examples of few commercially available composite insulators manufactured in China [4.16]. It can be seen that the required creepage is satisfied only by insulators longer than 3.2m. The additional benefit of polymeric insulators is their superior performance under pollution conditions due to their hydrophobicity properties. Such performance helps since the specific creepage used is that recommended by the standards for porcelain insulators.

The use of high voltage creepage extenders in glass insulator discs could also be an option for the uprated line. Such extenders increase the creepage length of the insulator string and improve the electrical strength by reducing leakage current and surface stress [4.17]. This may help in reducing flashover due to transients in the line. However, this would require laboratory tests and is beyond the scope of this thesis.

Table 4.6: Examples of few commercially available composite insulators [4.16].

System Voltage (kV)	No. of Sheds	Insulator Length (m)	Dry Arc Length (m)	Creepage Length (mm)
345	65	3.22	3.0	10100
345	65	3.32	3.0	11010
345	65	3.32	3.0	8970
400	81	3.92	3.7	12540
400	73	4.02	3.7	12690
400	81	4.02	3.7	11130
400	81	4.05	3.7	11130

The solutions described, so far, have focused on satisfying the minimum required phase-to-earth clearances at 400kV system as presented in Table 4.4. An alternative solution to this problem could be approached in the reverse way. Instead of satisfying the minimum required clearance for a specified overvoltage level, the value of minimum required clearance itself could be reduced by selecting a set of overvoltage withstand levels lower than 1425 / 1050kV (lightning / switching) commonly used for 400kV system in the UK. This would only be possible if the magnitude of overvoltages due to transients in the system could be reduced. In the following section, the opportunity to apply this unique alternative approach of reducing the requirement of air clearance in the line is investigated.

4.5 Reduction of the Required Minimum Phase-to-Earth Clearances

As previously stated, the required phase-to-earth clearance of an overhead line is determined mainly by the magnitude of overvoltages produced by lightning surges and switching events [4.18], and the overvoltage considerations for transmission lines operation above 245kV are governed mainly by switching surges [4.9, 4.19]. However, this general rule may not always apply as the electrical clearances for overhead lines above 245kV may also be influenced by the lightning surges. The extent of influence of the lightning and switching overvoltages depends upon the selected combination of lightning and switching withstand voltage levels. As outlined in Section 3.6.2, there are six possible different combinations of lightning and switching withstand levels for 400kV system.

For the case considered here for uprating 275kV line with 1050kV / 850kV (lightning / switching) withstand level to 400kV system, one set of overvoltage level must therefore be selected from these six different combinations. As seen in Figure 3.8 (Chapter 3), phase-to-phase clearance requirements for 400kV system are dictated only by switching overvoltage. However, for a withstand level of 1425kV / 1050kV (lightning / switching), which is generally used in the UK for 400kV system, the phase-to-earth clearance is equally dictated by switching and lightning overvoltages. The 275kV line considered here has a critical phase-to-earth clearance requirement for uprating, and therefore, both the lightning and switching overvoltages should be considered while determining clearance requirements.

The minimum required phase-to-earth clearance is 2.6m for 400kV system as given in Table 4.4 based on the withstand voltage level of 1425kV and 1050kV for lightning and switching overvoltage respectively. However, if the lightning withstand level is reduced to 1300kV, the clearance requirement for lightning overvoltage reduces from 2.6m to 2.4m. Furthermore, if the switching overvoltage level is reduced to 950kV, the clearance can be reduced to 2.2m. In this case, by reducing withstand voltage level to 1300kV / 950kV (lightning / switching) or below, the required phase-to-earth clearance can be reduced to values less than or equal to 2.4m. The available minimum phase-to-earth clearance of 2.48m in 275kV line would be sufficient for uprating to 400kV if this combination of overvoltage withstand level is adopted.

4.6 Limitation of Impulse Withstand Level

The overvoltage withstand level on a system can be limited by control of overvoltages due to lightning surges and switching events. Traditionally, lightning overvoltages are controlled by adding a shield wire, reducing ground resistance, adding counterpoise earth electrodes or increasing insulation in the system [4.20]. Switching overvoltages are conventionally controlled by using the point-on-wave switching technique or by the use of pre-insertion resistors in parallel with the line circuit breakers. However, these resistors make the circuit breaker mechanically more complex and, therefore, are not so popular due to concerns over circuit breaker reliability [4.21]. Also, the use of switch synch relays can reduce the switching overvoltage to some extent [4.22, 4.23]. However, this method is not always capable of reducing overvoltage level below the switching impulse withstand level [4.22]. An alternate solution is the application of line surge arresters along the line for limitation of overvoltages to below the system switching and lightning overvoltage withstand levels [4.24, 4.25]. The application of surge arresters along the line to control lightning and switching overvoltages is investigated in the following chapters; the computation of network overvoltages (Chapter 5) and application of surge arresters (Chapter 6).

4.7 Conclusions

In this chapter, electrical clearance issues for voltage uprating of an overhead transmission line were investigated. A particular design of 275kV transmission line used in the UK power network was selected for its possible uprating to 400kV. It was found that the available phase-to-earth clearance in a still air condition was the limiting condition for uprating the line to 400kV system. Replacement of an insulator with the same length as a standard 400kV insulator or increasing the length of existing insulator string by adding more insulator discs to provide additional creepage would infringe clearance requirements.

A solution was proposed involving the application of a 3.2m insulator to replace the existing 3.31m which would provide sufficient clearance for 400kV operation. However, the proposed shorter insulator would require an additional creepage of 3456mm. The use of a composite polymer insulator which can provide high creepage was proposed as practical solution to this problem.

As an alternate solution, it was proposed to limit the overvoltage level allowing a lower standard lightning / switching withstand level and a correspondingly lower clearance requirement. For increased reliability of the line and to limit the overvoltage of the system, application of line surge arresters was recommended.

CHAPTER 5

COMPUTATION OF TRANSIENT OVERVOLTAGES ON SELECTED NETWORK FOR VOLTAGE UPRATING

5.1 INTRODUCTION

In Chapter 4, it was proposed to uprate an overhead line by reducing its overvoltage level with the help of surge arresters. In particular, the application of line surge arresters would be to control the overvoltage to reduce the minimum phase-to-earth clearance. Metal oxide surge arresters were developed in 1980s, and are widely used for overvoltage protection of power systems. Examples of surge arrester applications to improve lightning and switching performances can be found in [5.1 – 5.6]. However, the application of surge arresters for uprating of overhead lines is not reported in the literature.

In this chapter, the overvoltages produced as a result of switching operations and lightning strikes are investigated. Firstly, the application of surge arresters for switching overvoltage control is considered. The results obtained from a parallel collaborative study on surge arrester application for control of switching overvoltage (under the same Engineering and Physical Sciences Research Council (EPSRC) project on "Uprating of Overhead Lines") is presented. Then, the overhead line is modelled for computation of lightning overvoltages and the applications of line surge arresters are investigated. The electrogeometric model is used to determine lightning termination statistics. The lightning overvoltage magnitude, the impulse waveshape due to shielding failure and backflashover are computed.

5.2 CONTROL OF SWITCHING OVERVOLTAGE

The switching overvoltage studies were carried out on the 275kV overhead transmission line under study using the ATP/EMTP (Alternative Transients Program / Electromagnetic Transient Program) [5.8]. The program allows modelling a large number of power system components and performing different transient analyses.

5.2.1 Line Parameters

The same double circuit 275kV line is considered in this study as described in Section 4.2.1. However, 'L3' towers of different heights are used here in different sections of the line to represent more closely the actual operational line. The line is 35km long with an average span of 300m. The line is modelled with twin 300mm^2 'Upas' AAAC conductors for the phase conductors and a 160mm^2 AACSR conductor for the earth wire. Glass insulator discs with total insulator string length of 3.31m are assumed.

5.2.2 Transmission Line Model for EMTP Simulation

The transmission line model is divided into 8 sections of different length based on the height of the 'L3' tower. Table 5.1 shows the details of the tower type and length of each section in the line. The structure of some typical intermediate towers (L3DE16, L3DE8, L3D Standard) in the line is shown in Figure 5.1.

The EMTP model of the line uses the J. Marti model [5.9] which is the most commonly used model for transient simulation. The frequency dependent J. Marti model for transmission line approximates the line surge impedance and the propagation constant by a rational function [5.9].

Table 5.1: Description of line sections used for simulating 35km long transmission line.

Line Section	Type of L3 Tower	Height of the Tower	Length of Line Section (km)
1	L3 D Standard	33.6	5.00
2	L3 D Standard	33.6	5.66
3	L3 DE8	38.7	5.97
4	L3 D10	37.3	2.63
5	L3 D30	36.8	3.18
6	L3 DE16	42.0	5.19
7	L3 DE24	42.0	1.03
8	Other Standard L3	46.7	6.00

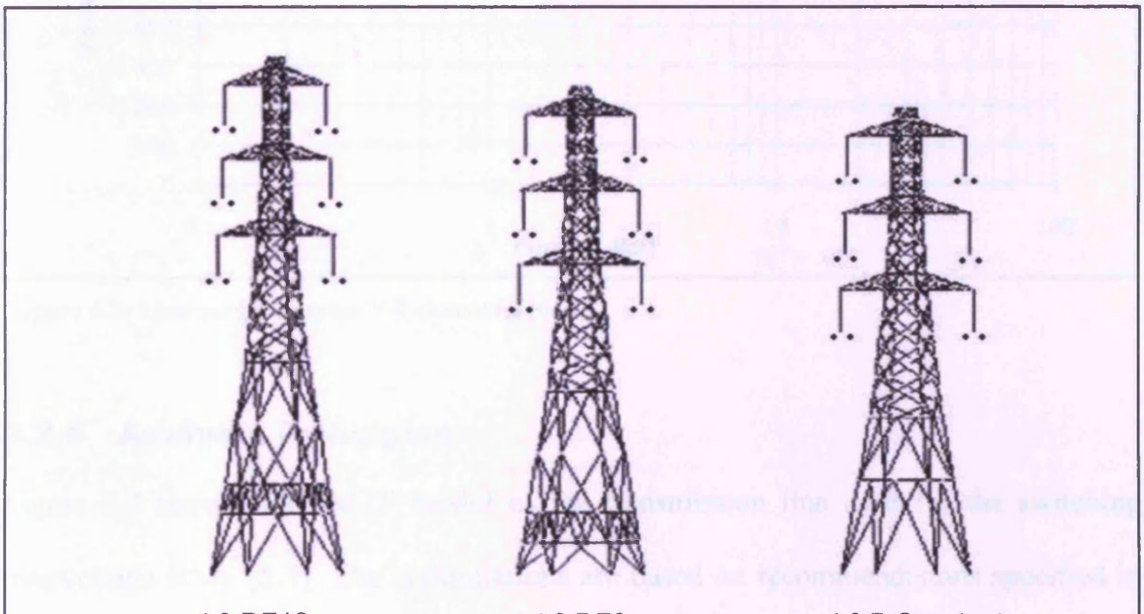


Figure 5.1: Structure of few 'L3' intermediate towers listed in Table 5.1 (PLS-CADD Model).

5.2.3 EMTP Surge Arrester Model

The line surge arresters are modelled in EMTP as per their V-I characteristics. Polymer-housed metal-oxide surge arresters with the ABB specifications as shown in Table 5.2 were used [5.10]. The voltage-current characteristic of the arrester is shown in Figure 5.2.

Table 5.2: Specifications for the metal oxide surge arresters [5.10].

Parameters	Description
Nominal discharge current	10 kA_{peak}
Rated voltage	360 kV
Maximum Continuous Operating Voltage (MCOV)	291kV
Energy capability	7.8 kJ/kV of rated voltage

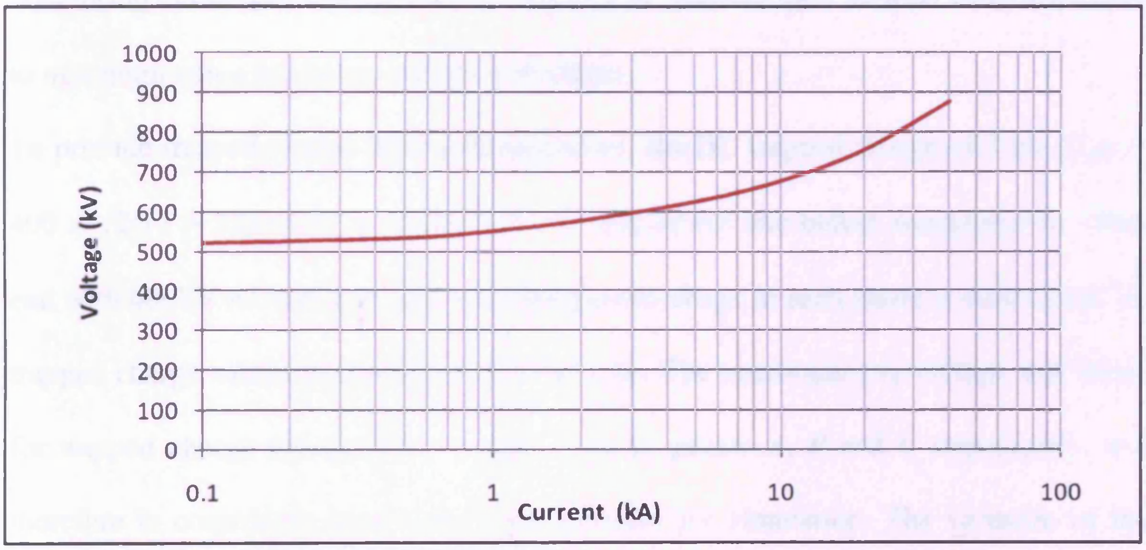


Figure 5.2: Line surge arrester V-I characteristic.

5.2.4 Analysis Principles

Figure 5.3 shows the EMTP model of the transmission line used for the switching overvoltage study [5.7]. The computations are based on recommendations specified in IEC 60071-2 [5.11].

Switching overvoltages on transmission line are produced due to opening and closing operations of circuit breakers under fault and also on line energisation and re-energisation. Line re-energisation with trapped charge will produce the worst case overvoltages. Therefore, to obtain the worst case scenario, the three-phase circuit breaker closing is modelled such that the closing occurs at voltage peak and maximum trapped charge with opposite polarities in all three phases. The circuit breaker closing is

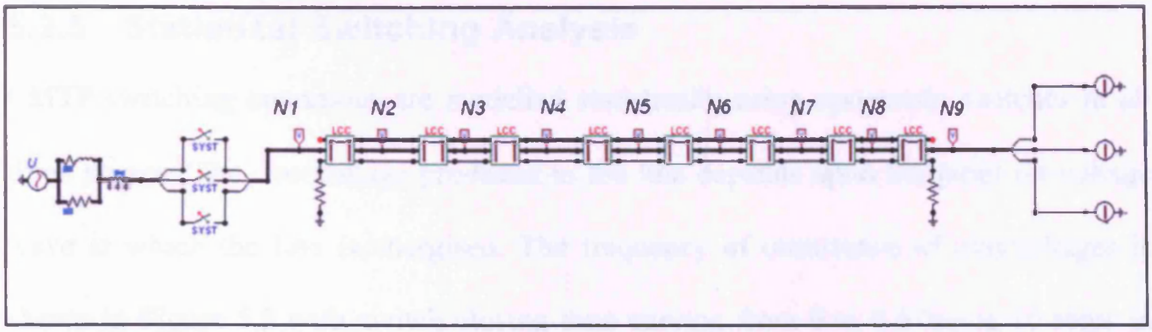


Figure 5.3: EMTP model for the switching analysis [5.7].

done using systematic switches which operate in constant time interval from maximum to minimum value in system voltage waveform.

To provide trapped charge during energisation, the DC trapped charge of 1 pu (1 pu = 400 × √2/√3 = 326.6kV) is applied on one end of the line before energising the other end with 400kV AC voltage. The switching overvoltage in each phase is determined for trapped charge values in the range of -1 to 1 pu. The maximum overvoltage was found for trapped charge values of -1, 1 and -1 pu in phases *A*, *B* and *C* respectively, and therefore is considered as a worst case scenario for simulation. The variation of the trapped charge for the 400kV transmission line for worst case is shown in Figure 5.4.

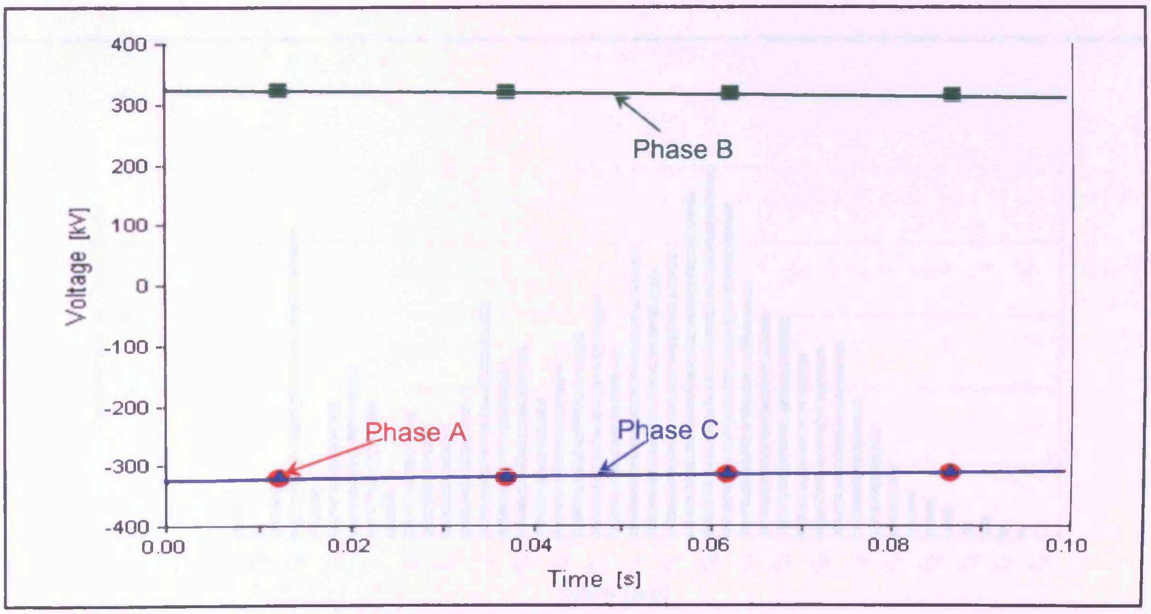


Figure 5.4: Trapped charge modelling for worst case scenario using EMTP (reconstructed from [5.7]).

5.2.5 Statistical Switching Analysis

EMTP switching operations are modelled statistically using systematic switches in all three phases. The overvoltage produced in the line depends upon the point on voltage wave at which the line is energised. The frequency of occurrence of overvoltages is shown in Figure 5.5 with switch closing time varying from 0 to 6.67ms in 10 steps in each phase giving rise to total of 1000 switching operation for 1/3rd of the voltage waveshape [5.7]. The maximum overvoltage of 3.5pu and the minimum overvoltage of 1.3pu are observed. The maximum overvoltage occurs at phase *B* while closing the switch at V_{max}. Figure 5.6 shows the overvoltage waveshape for the maximum overvoltage obtained in this case [5.7]. This overvoltage occurs with the systematic switch closing time as shown below:

- Phase A : 15.36ms
- Phase B : 16.03ms
- Phase C : 15.36ms

The maximum overvoltage obtained here is 3.5pu × 326.6 = 1143kV. This value exceeds the switching overvoltage protection level of 1050kV normally adopted for

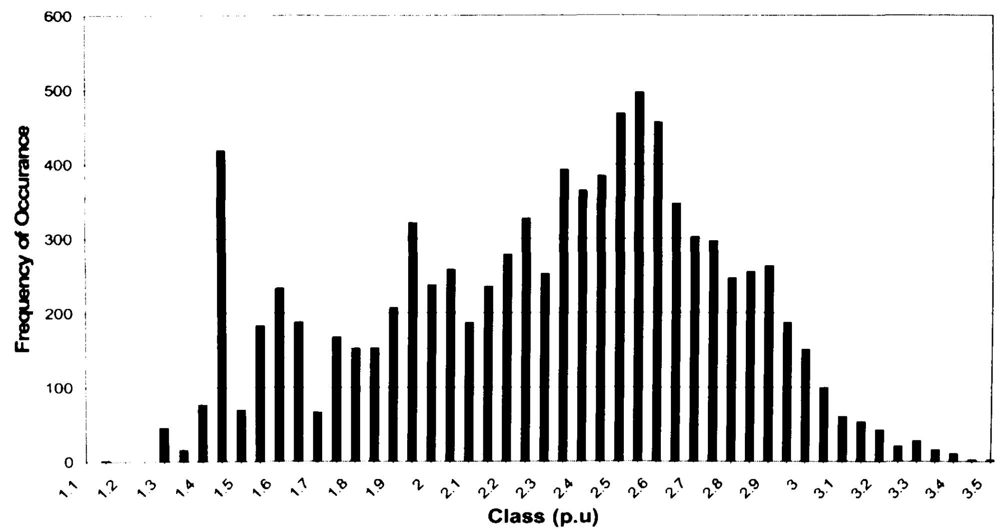


Figure 5.5: Distribution of overvoltage along the line (Trapped charge = -1 pu) [5.7].

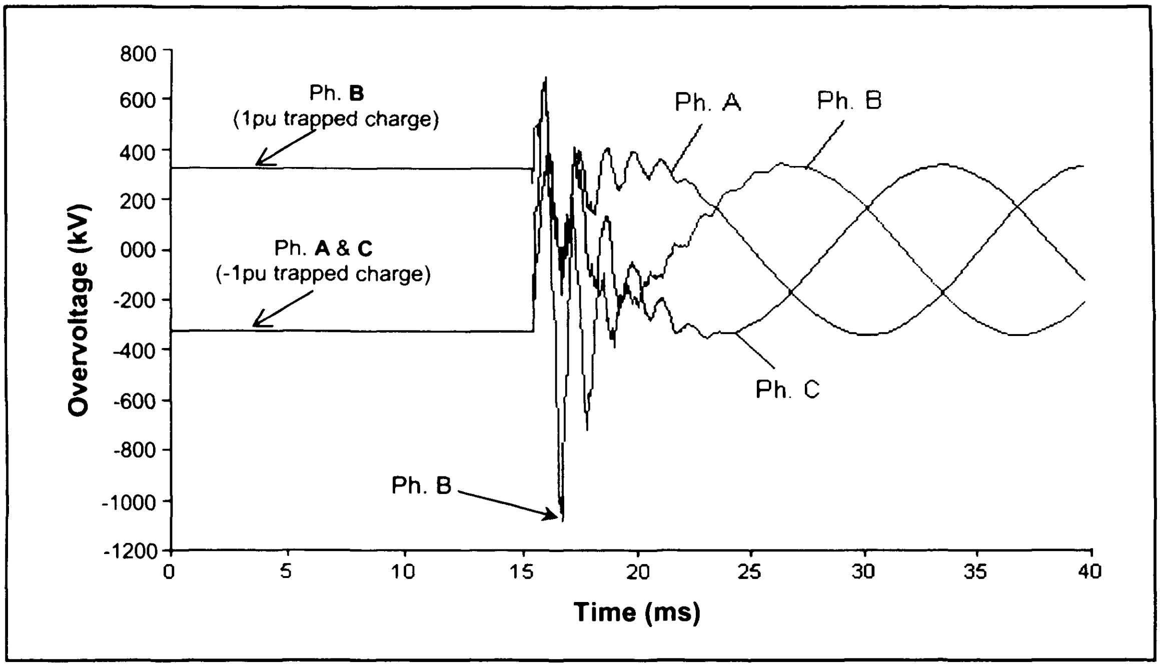


Figure 5.6: Overvoltage waveshape in three phases (reconstructed from [5.7]).

designing 400kV system in the UK. In practical situation, the trapped charge may go up to 1.25pu. The maximum switching overvoltage in this case will further rise. Therefore, it is essential to limit these overvoltages.

5.2.6 Limitation of Switching Surges on Overhead Lines using Surge Arrester

The application of transmission line surge arresters offers an efficient alternative to other conventional methods of switching overvoltage control. From the economic point of view, it is important to identify the appropriate locations and configuration of arresters on the line so that the required control of the overvoltage can be obtained with the minimum number of arrester units. The overvoltages along the line are calculated for different arrester configurations to optimise the number of surge arresters. The following arrester configurations are considered.

- Configuration **A** : No arresters
- Configuration **B** : Arresters only at the line ends (Nodes *N1* and *N9*)

– Configuration **C** : Arresters at line ends and in the middle of the line (Nodes *N1*, *N9* and *N5*)

– Configuration **D** : Arresters at every alternate node (Nodes *N1*, *N3*, *N5*, *N7* and *N9*)

The line is energised at node *N1* and the maximum overvoltages are recorded at all the nodes along the line and plotted in Figure 5.7 [5.7]. The switching conditions remain the same as explained in Section 5.2.5 and the simulations were carried out with trapped charge in the system representing worst case scenario. When the line is not protected with arresters (configuration A), it is observed that the switching overvoltage magnitude increases along the line as it gets close to the open end and reaches maximum value of 3.5pu at node *N9*. The optimum overvoltage reduction at each node is obtained with arresters at every alternate node. In this case, except node *N8*, overvoltages in all other nodes are reduced down to 1.7pu.

With reference to Figure 5.7, the maximum switching overvoltage can be reduced from 3.5pu (1143kV) to 2.05pu (669.5kV) in configuration *B*, i.e. with surge arresters applied

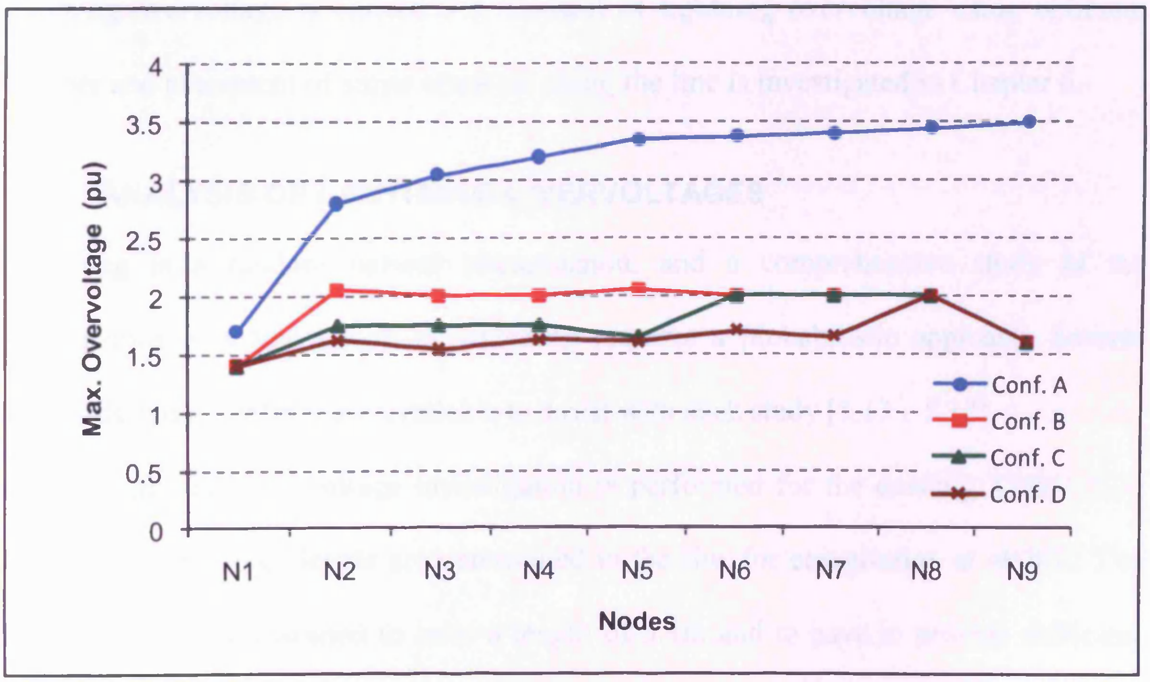


Figure 5.7: Overvoltage along the line for different arrester configurations (reconstructed from [5.7]

at the line ends only. This would be sufficient to allow a switching impulse withstand level of 850kV for the uprated 400kV application and, thereby, allowing a reduction in the minimum phase-to-earth clearance requirements from 2.6m to 1.8m for switching overvoltages. The possibility of 850kV withstand level is even better than targeted value of reducing required clearances to 2.2m by controlling withstand level to 950kV. By adding one more set of arresters in the middle of the line (Configuration *C*) or with arresters at alternate towers (Configuration *D*), the overvoltages are not further reduced significantly compared with configuration B. Therefore, it would be uneconomical to choose configuration *C* or *D*.

Accordingly, configuration *B* is the best choice for control of switching overvoltages. However, surge arresters applied at line ends alone will not help to control lightning overvoltages along the line. It is expected that lower values of lightning withstand level can only be adopted when the line is protected by closely spaced surge arresters throughout the line [5.12]. However, application of large numbers of surge arresters along the line may not be economical. In the following sections, an investigation of lightning overvoltage is carried out. Control of lightning overvoltage using optimum number and placement of surge arresters along the line is investigated in Chapter 6.

5.3 Analysis of Lightning Overvoltages

Lightning is a random natural phenomenon, and a comprehensive study of the performance of a line struck by lightning requires a probabilistic approach. Several standards and guidelines are available to assist with such study [5.13 – 5.15].

Here, a lightning overvoltage investigation is performed for the existing 275kV 'L3' line. The overvoltage levels are determined in the line for energisation at 400kV. The line insulators are assumed to have a length of 3.3m and to have to provide sufficient creepage for 400kV operation.

The lightning events producing overvoltages in the line are as a result of a stroke hitting:

- a tower / earth wire (backflashover) or,
- direct strike to the phase conductor (shielding failure)

The application of line surge arresters is considered to control the overvoltages.

5.4 Simulation Tools for Lightning Study

Different software is available for studying lightning and its performance in overhead power line. These include IEEE FLASH, Anderson and Thompson's digital weather model DCORTL, SIGMA-Slp, EPRI TFlash, and the Electromagnetic transient program EMTP. In this study, the SIGMA-Slp [5.16] and the EPRI program, TFlash [5.17] are used.

5.4.1 SIGMA-Slp [5.16]

SIGMA-Slp is a windows-based software designed for the determination of transmission line electrical performance with special reference to the application of surge arresters. This program is used because it can model single and multiple circuit lines using Monte-Carlo simulation (see Appendix A) of lightning performance [5.16] and uses the Electrogeometric model (EGM) for determination of stroke termination. Electromagnetic transients on the line are computed by the multiphase travelling wave method. The calculation technique in this program follows recommendations made by CIGRE WG 33-01 [5.14] and IEEE Working Group [5.18, 5.19]. The program can simulate line performance of both shielded and unshielded transmission line. The software is specially designed to permit rapid and simple determination of an optimum line surge arrester installation scheme. The program output provides statistical representation of expected line flashover performance and expected energy absorption by the arresters. Shielding failure simulation is based on graphical representation of the conductor striking distances. SIGMA-Slp can also calculate electric and magnetic field profiles for the conductor configurations.

5.4.2 TFlash [5.15]

TFlash is a comprehensive transmission line lightning performance simulation program developed by EPRI. The program evaluates all aspects of lightning reliability and includes a large library of line geometries, insulator types, arresters, conductors, grounding, transmission voltage etc. The software can simulate multiple lines on a single wayleave and has the facility to use the EGM or the EPRI stroke attraction model (see Appendix B). With reference to Figure 5.8, the program has two major components. The first component is where users build a model of the line to be

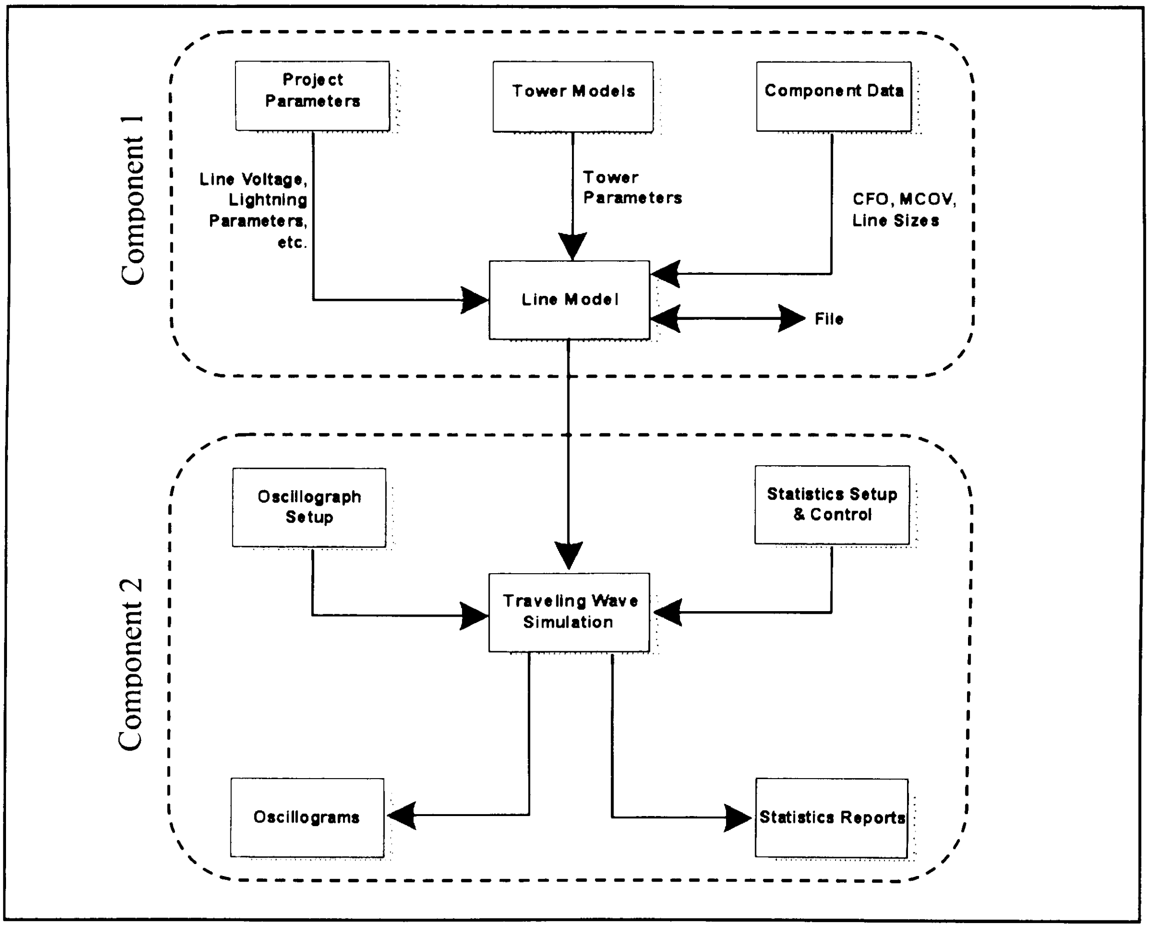


Figure 5.8: TFlash program structure [5.15].

analysed. The second component takes data from the line model and builds the electrical model for the travelling wave simulation and creates reports.

5.5 LINE MODELLING FOR COMPUTATION OF LIGHTNING OVERVOLTAGE

Much literature has been published concerning the modelling of transmission line components for lightning overvoltage simulation [5.14, 5.18 – 5.23]. In this study, models of the existing 275kV line components were set up in SIGMA-Slp and TFlash. The models require the selection of towers, conductors, insulators, earth type and arresters. Using this data, electrical models of a short section of the line are constructed. The programs simulate lightning current attachment to the line and the propagation of the current along the line and towers. The details of modelling process are explained in the following sections.

5.5.1 Line Model

Each span on the transmission line is represented as a multiphase untransposed distributed parameter line section. In order to avoid reflections in the line, a sufficiently long section is added to each side of the line length considered for simulation. In addition, at the line ends, SIGMA-Slp connects coupling matrices while TFlash adds matching impedances. Each simulated span section is further divided into shorter sub-sections to enable stroke simulation at a number of points along the span.

5.5.2 Tower Model

The EPRI TFlash program models a high voltage transmission tower as a network of short transmission lines carrying transient current from its top to the earth and its reflection back towards the top [5.15]. Therefore, in TFlash, tower is modelled as a short vertical transmission line section with constant surge impedance and earthed through its footing resistance at the end. In SIGMA-Slp, the tower is modelled by a simple propagation element model represented by the tower surge impedance (Z_T) and its propagation length (l_{prop}) as shown in Figure 5.9a. The propagation length is equal to the height of the tower (h_T).

The surge impedance of the steel lattice tower used in both programs is calculated using the same CIGRE model shown in Figure 5.9b using Equations (5.1) and (5.2) [5.14].

$$Z_T = 60 \ln \cot \left[0.5 \tan^{-1} \left(\frac{r_{avg}}{h_1 + h_2} \right) \right] \tag{5.1}$$

$$r_{avg} = \frac{r_1 h_2 + r_2 (h_1 + h_2) + r_3 h_1}{(h_1 + h_2)} \tag{5.2}$$

Where,

Z_T is tower surge impedance and r_{avg} is the weighted average tower radius. h_1 and h_2 are the tower height from base to midsection and midsection to tower top respectively. r_1, r_2, and r_3 are the radii at the top, midsection and base of the tower respectively. Figure 5.9b shows these dimensions with corresponding values for the 'L3' tower structure. The computed value of tower surge impedance is 173.1Ω.

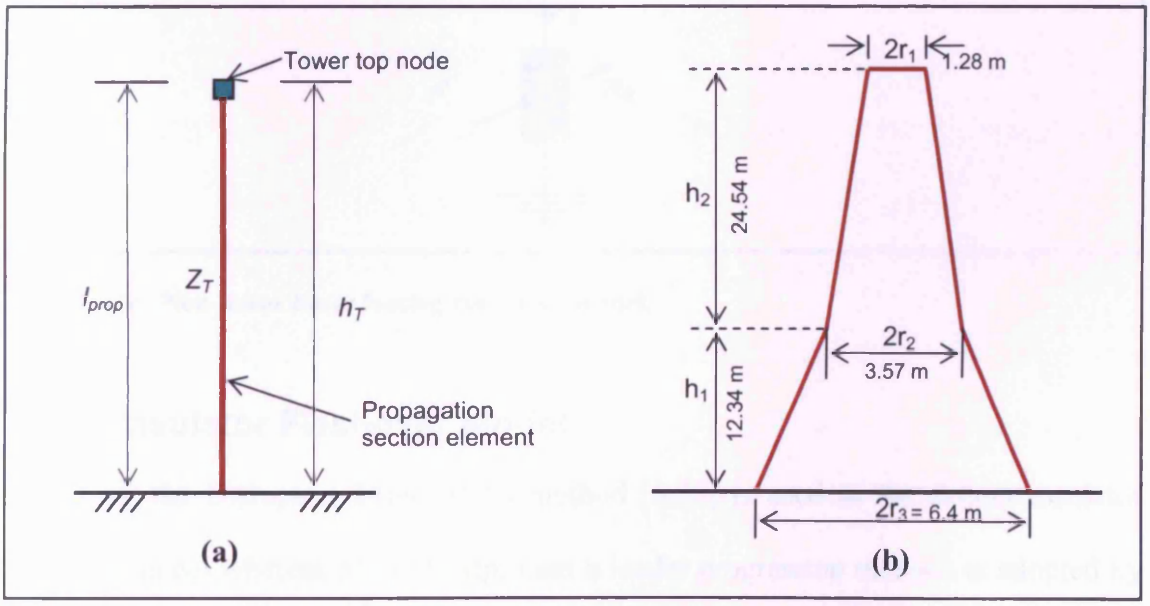


Figure 5.9 : Tower models a) Simple propagation element model in SIGMA-Slp and b) Assumed model geometry for computation of tower surge impedance in both SIGMA-Slp and TFlash.

5.5.3 Tower Footing Resistance Model

A non-linear tower footing resistance model as shown in Figure 5.10 is used in both SIGMA-Slp and TFlash. The footing resistance (R_T) is calculated using Weck's equation, as given in Equation (5.3) [5.24].

$$R_T = \frac{R_0}{\sqrt{1 + \frac{I}{I_g}}} \tag{5.3}$$

where;

R_0 = Low current tower footing resistance (Ω)

I = Lightning stroke current through tower footing impedance (Ω)

I_g = soil ionisation limiting current (kA) and is calculated using Equation (5.4)

$$I_g = \frac{E_0 \, \rho}{2\pi \, R_0^2} \tag{5.4}$$

where;

ρ = soil resistivity (Ω-m),

E_0 = soil ionisation critical electrical field (4 kV/cm)

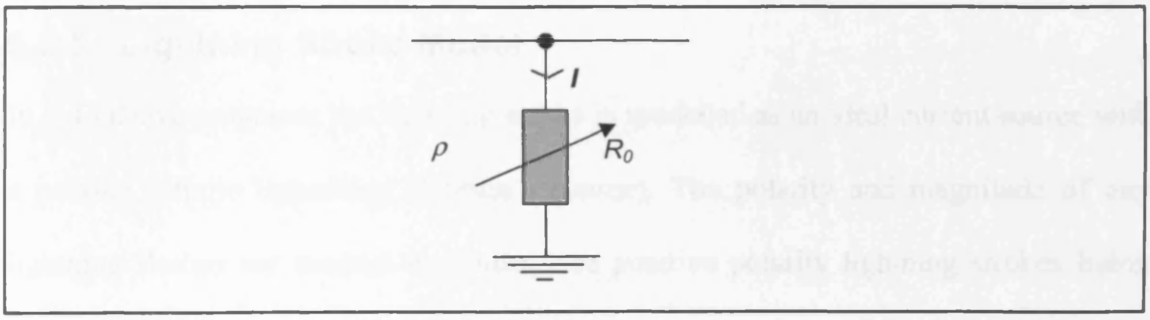


Figure 5.10 : Non-linear tower footing resistance model.

5.5.4 Insulator Flashover Model

In TFlash, the Disruptive Effect (DE) method [5.25] is used as the default insulator flashover model whereas SIGMA-Slp, uses a leader progression method as adopted by CIGRE [5.14].

The DE method defines the disruptive index by:

$$DE = \int [V(t) - A]^B \, dt \tag{5.5}$$

Where, $V(t)$ is the instantaneous value of the impulse voltage, and A and B are constants. A represents the minimum voltage below which breakdown cannot occur and B is a coefficient indicating that the breakdown process is not linear. When the disruptive index reaches a critical value, breakdown would occur.

The leader progression method is represented by:

$$V_l = 170\, d \left[\frac{u(t)}{d - l_l} - E_0\right] e^{0.0015 \frac{u(t)}{d}} \tag{5.6}$$

Where, V_l is the leader velocity, d the gap distance, l_l the leader length, $u(t)$ the applied voltage and, E_0 the voltage gradient (520kV/m). In this model, the flashover mechanism follows three steps: corona inception followed by streamer propagation and leader progression. When the leader crosses the phase-to-earth air gap, flashover occurs.

5.5.5 Lightning Stroke Model

In both above programs, the lightning stroke is modelled as an ideal current source with a parallel infinite impedance (Norton's source). The polarity and magnitude of any lightning flashes are random in nature. The positive polarity lightning strokes being very rare (hardly exceeding 10% of the total ground flash [5.26]), the lightning current waveform model of a negative return stroke approximated by CIGRE [5.14] and IEEE [5.26], as reproduced in Figure 5.11, is used in this study. Table 5.3 shows the statistical parameters of the negative return stroke used [5.14, 5.26].

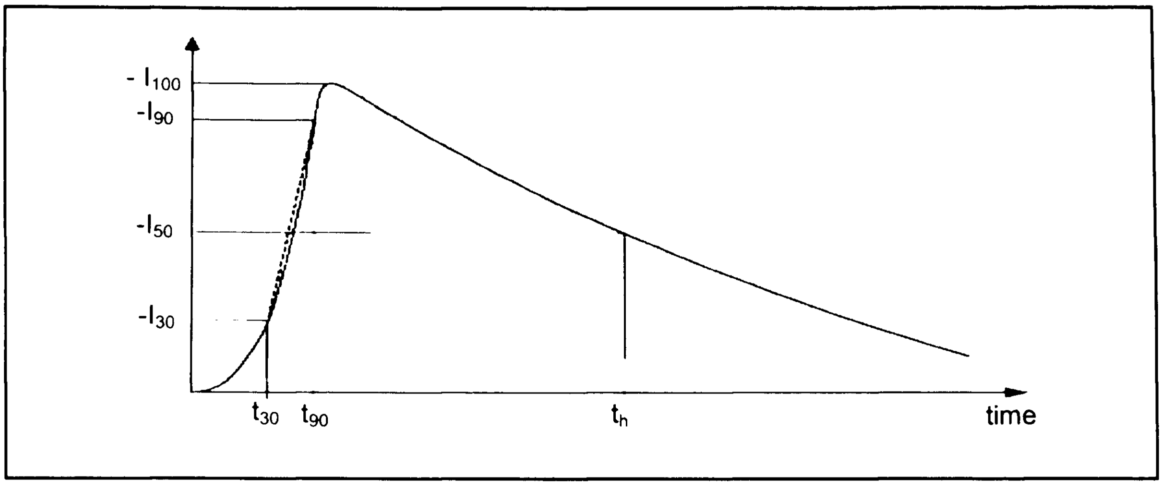


Figure 5.11 : Negative return stroke lightning waveform.

Table 5.3: Statistical parameter of negative return stroke [5.14, 5.26].

Parameter	Median Value	Logarithmic Standard Deviation (Base *e*)
Front time (t_f) (μs)	4	0.55
Tail time (t_h) (μs)	77.5	0.58

5.5.6 Stroke Attraction Model

In both programs, the Electrogeometric Model (EGM) is used to determine the lightning strike point on the line. Figure 5.12 shows a basic concept of this model for determining the striking distance. As the leader approaches the transmission line, each conductor emits an upward leader with a striking distance R. If the downward leader falls on area A, a strike to the shield wire occurs. If it falls on area B, a shielding failure occurs; if it ends up in area C, it strikes to earth. The conductor, and earth striking distances used in the programs are given by [5.13, 5.14]:

$$R_s = R_p = 10\, I^{0.65} \tag{5.7}$$

$$R_e = [3.6 + 1.7\, \ln(43 - h)]\, I^{0.65} \qquad for\;\; h < 40m \tag{5.8}$$

$$R_e = 5.5\, I^{0.65} \qquad for\;\; h > 40m \tag{5.9}$$

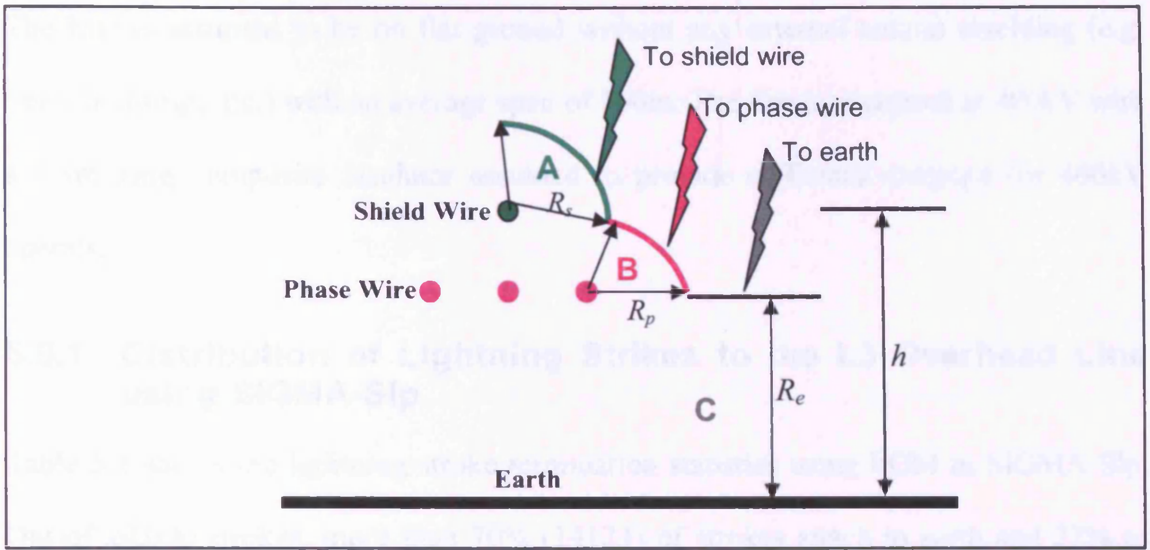


Figure 5.12 : Electrogeometric model for determination of stroke point.

Where, R_s is the striking distance to the shield wire, R_p is the striking distance to the phase conductor, R_e is the striking distance to earth, I is the lightning impulse current magnitude and, h is the height of the tower.

5.6 DETERMINATION OF LIGHTNING STROKE TERMINATION STATISTICS USING THE ELECTROGEOMETRIC MODEL

In order to set appropriate parameters of the lightning stroke and to understand its random behaviour for overvoltage calculation, the lightning stroke termination statistics are determined using the Electrogeometric model (EGM) in SIGMA-Slp and TFlash.

In SIGMA-Slp, random lightning strokes are generated with magnitudes between 1.2kA and 161.1kA to accommodate both shielding failure and backflash, and with rise times in the range from 1.2μs and 4.38μs. A total of 20,000 lightning strokes are used with the impulse shape varying randomly within 2000 samples. In TFlash, however, the stroke current range can be selected between 1kA and 300kA, and the range is divided up to 512 current 'bins'. In order to match the two models as closely as possible, 32 stroke current bins and a peak current range from 2.5kA to 160kA were selected in TFlash.

The same double circuit 'L3' line as described in Section 4.2 is considered in this study.

The line is assumed to be on flat ground without any external natural shielding (e.g. trees, buildings etc.) with an average span of 300m. The line is energised at 400kV with a 3.3m long composite insulator assumed to provide sufficient creepage for 400kV operation.

5.6.1 Distribution of Lightning Strikes to the L3 Overhead Line using SIGMA-Slp

Table 5.4 shows the lightning stroke termination statistics using EGM in SIGMA-Slp. Out of 20,000 strokes, more than 70% (14123) of strokes attach to earth and 27% of strokes are collected by the shield wire (4827) and tower tops (521). Only about 3% (529) of the strokes are predicted to hit the phase conductor. Out of the strokes that are collected by phase conductors, 100% attach to the top two phases (A_1 and C_2).

Figure 5.13 further shows EGM results that help to understand the distribution of

Table 5.4: Distribution of stroke termination along the line using EGM in SIGMA-Slp.

			% of total stroke
Ground flash density	GFD (str/km^2/yr)	1	
Number of strokes collected by the line	N_L (Strokes)	11.3	
Median of the stroke collected by the line	I_{med} (kA)	31.4	
Total stroke	Strokes_Tot	20000	
Number of strokes to earth	To Earth	14123	70.62%
Number of stroke to tower top	To Tower top	521	26.75%
Number of stroke to shield wire	To Shield wire	4827	
Number of strokes to phase conductors	To Phase A1	254	2.65%
	To Phase B1	0	
	To Phase C1	0	
	To Phase C2	275	
	To Phase B2	0	
	To Phase A2	0	

lightning currents responsible for shielding failure and backflashover in the line. With reference to Figure 5.13a, of those which hit phase conductors, the lightning current magnitude up to 30kA has a high probability of hitting a phase conductor. An average current magnitude of 22.6kA with a standard deviation of 12.5kA is calculated for strokes causing shielding failure in the line. It is also observed that the magnitude of the stroke current causing shielding failure is higher than 50kA. The distribution of current hitting tower tops or a shield wire is shown in Figure 5.13b. As can be seen in the figure, high magnitude currents (up to 150kA) are likely to hit tower tops or a shield wire that could cause backflashover. However, the probability of very high magnitude current hitting the phase conductor is less for high magnitude strokes.

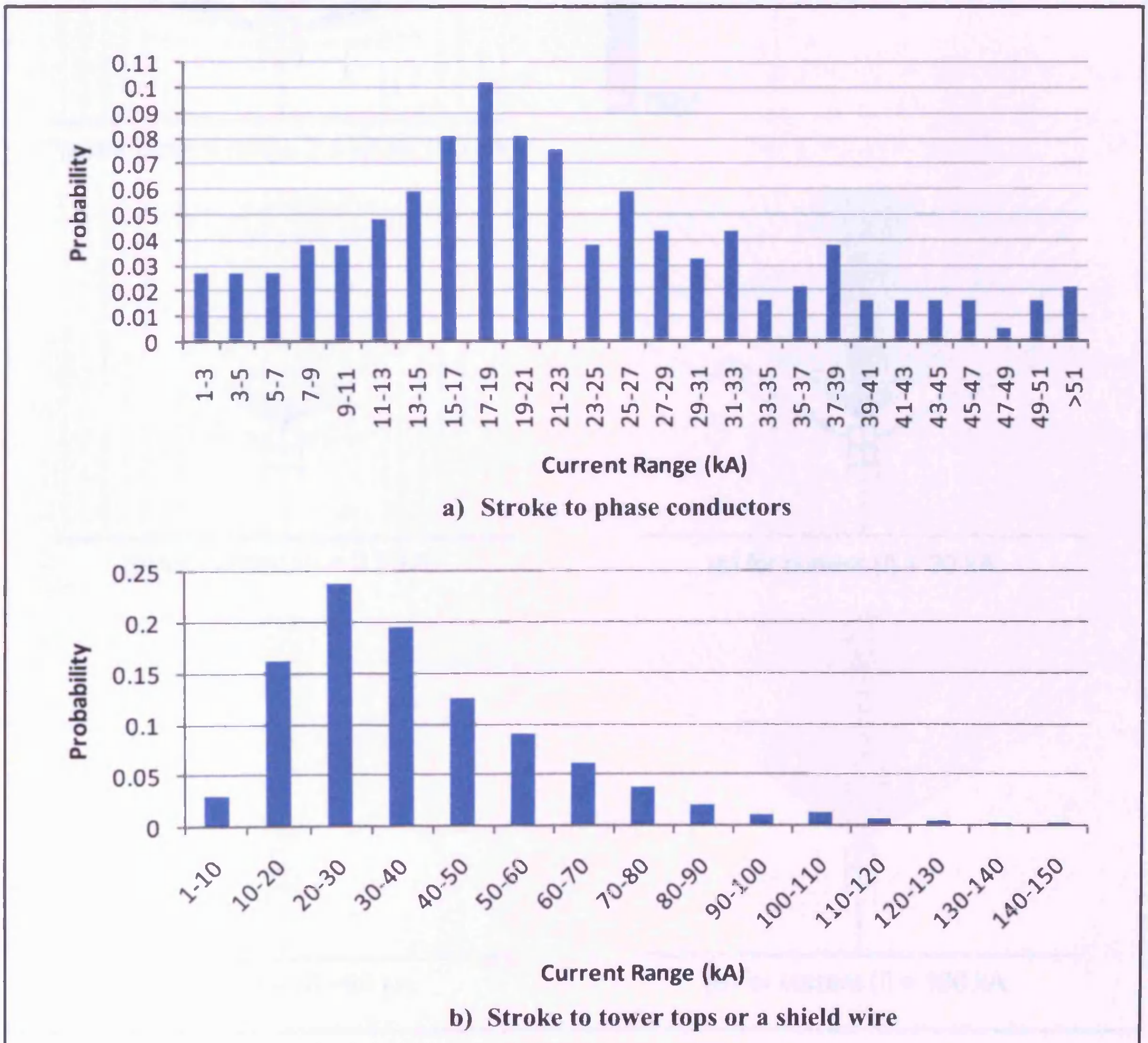
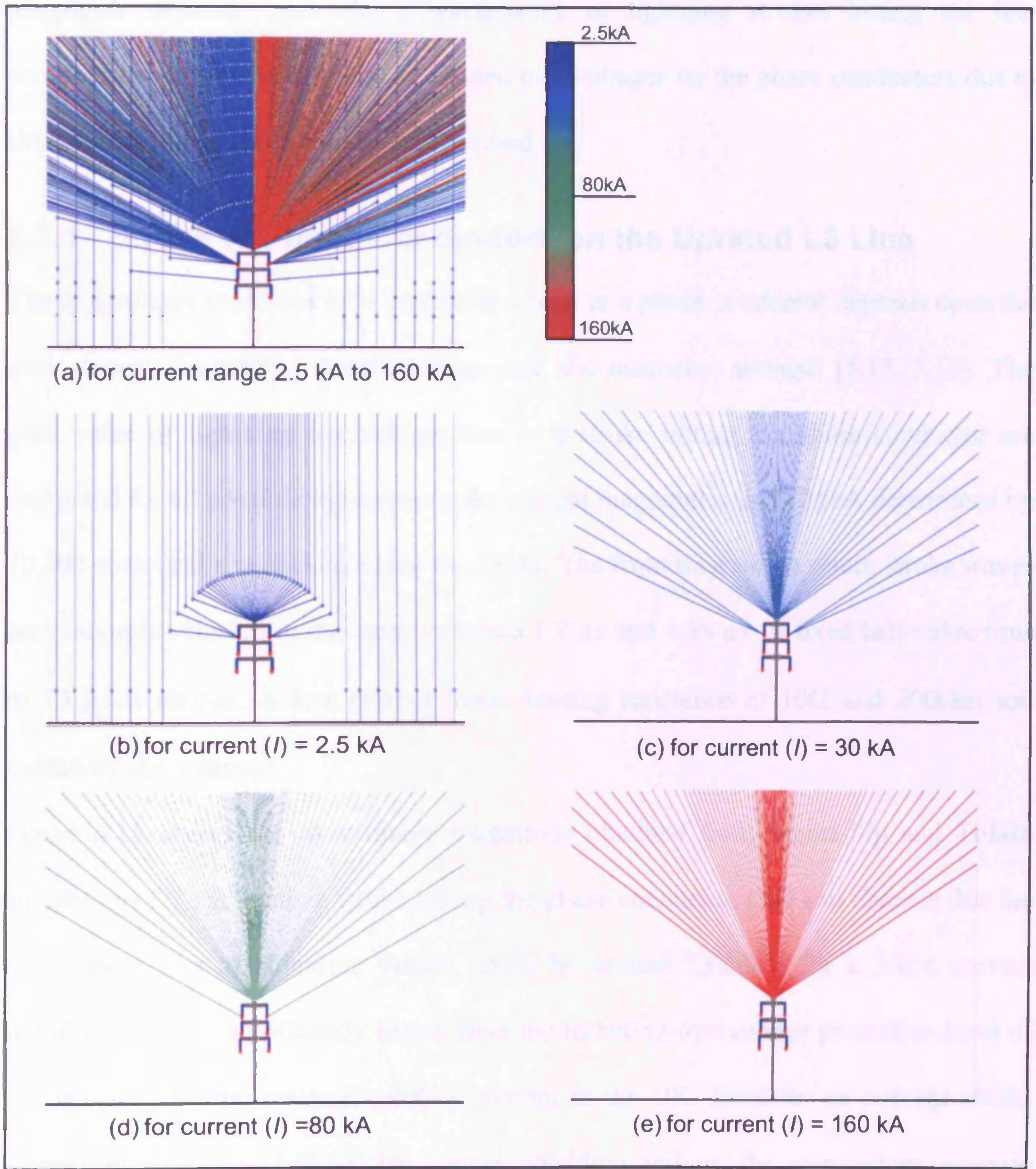


Figure 5.13: Distribution of lightning stroke currents along the line (SIGMA-Slp simulation).

5.6.2 Distribution of Lightning Strikes to the L3 Overhead Line using TFlash

The stroke termination statistics obtained using the EGM in TFlash program are closely similar to the results obtained with SIGMA-Slp simulations. Figure 5.14 shows a pictorial distribution of stroke termination for different stroke current values. As seen in the figure, the majority of strokes attaching to the line terminate at the tower tops or shield wire. More than 95% of strokes to phase conductors, hit the top two phases only.



(a) for current range 2.5 kA to 160 kA

(b) for current (I) = 2.5 kA

(c) for current (I) = 30 kA

(d) for current (I) =80 kA

(e) for current (I) = 160 kA

Figure 5.14 : Distribution of stroke termination for different values of lightning current simulated in TFlash.

Figure 5.14 also indicates that, for this design of line, a single shield wire present is not sufficient to protect the line from direct phase strikes as currents up to 80kA magnitude can hit the phase conductors.

5.7 LIGHTNING OVERVOLTAGES IN THE UPRATED L3 LINE

Lightning overvoltages produced in an overhead line result from the stroke hitting the phase conductors (shielding failure) or the shield wire (backflashover). The overvoltage magnitude depends upon the characteristics of lightning strokes hitting the line components. In this section, the computed overvoltages on the phase conductors due to shielding failure and backflash are described.

5.7.1 Stroke to Phase Conductors on the Uprated L3 Line

The overvoltage produced by a particular stroke to a phase conductor depends upon the peak current magnitude, system voltage and the insulation strength [5.13, 5.14]. The peak value of lightning overvoltage due to a stroke hitting the phase conductor are computed for all possible lightning stroke current magnitudes up to 30kA determined by 20,000 statistical simulations using the EGM. The front time of the return stroke waves are randomly selected in the range between 1.2 μs and 4.38 μs. A fixed half-value time of 75 μs is chosen. A low current tower footing resistance of 10Ω and 200Ωm soil resistivity are assumed.

Figure 5.15 shows the overvoltage magnitude obtained from Sigma-Slp and TFlash simulations for each return stroke hitting the phase conductor. One can observe that the overvoltage due to shielding failure could be around 5,000kV for a 30kA current impulse which is significantly higher than the lightning overvoltage protection level of 1425kV required normally for 400kV system in the UK. Even for an average stroke current magnitude (22.6kA) that causes shielding failure, the overvoltage exceeds

4,000kV and only impulse current magnitudes less than 6kA would produce overvoltages that fall within the protection level of the system. The figure also shows the possibility of insulation flashover due to shielding failure for stroke currents more than 11kA. Figure 5.16 shows a typical overvoltage shape for a 22.6 kA, 4/77.5 impulse shape striking a phase conductor causing flashover across the insulator. The TFlash model predicts a faster initial rise time causing early flashover resulting in lower overvoltage magnitude compared with the Sigma-Slp model.

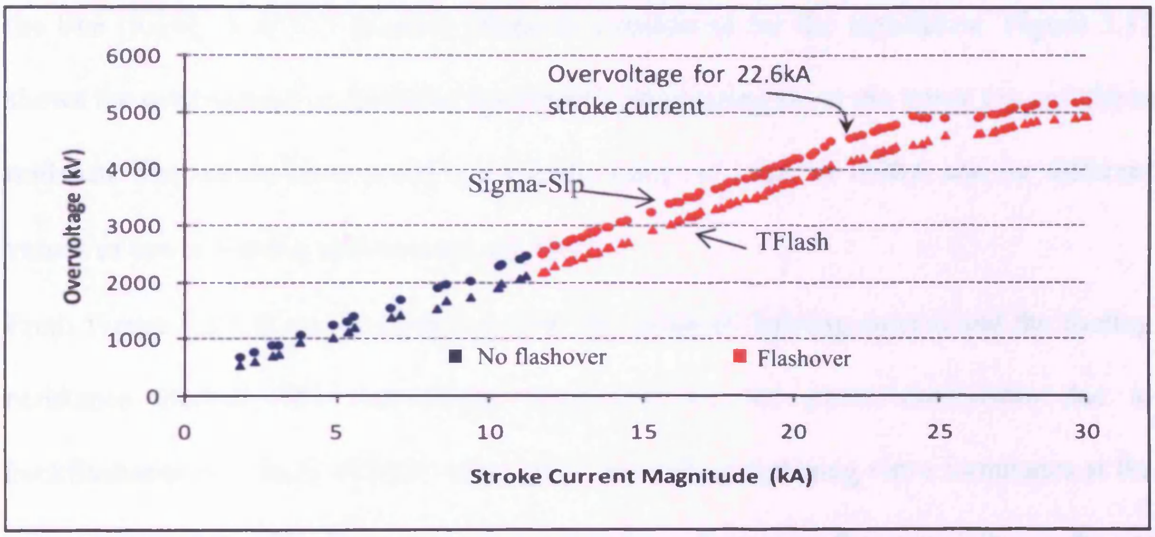


Figure 5.15: Overvoltage for lightning stroke currents causing shielding failure.

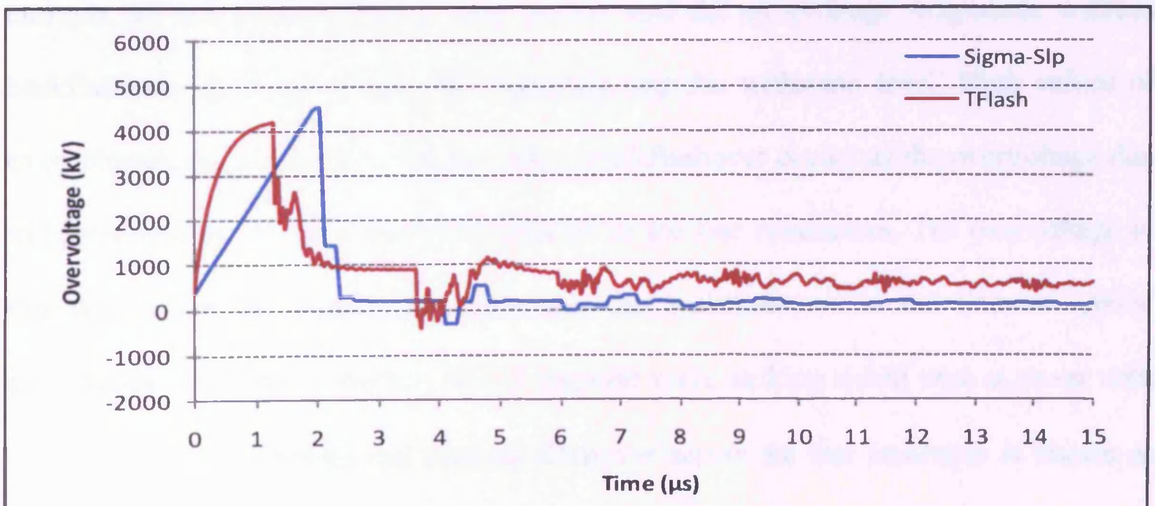
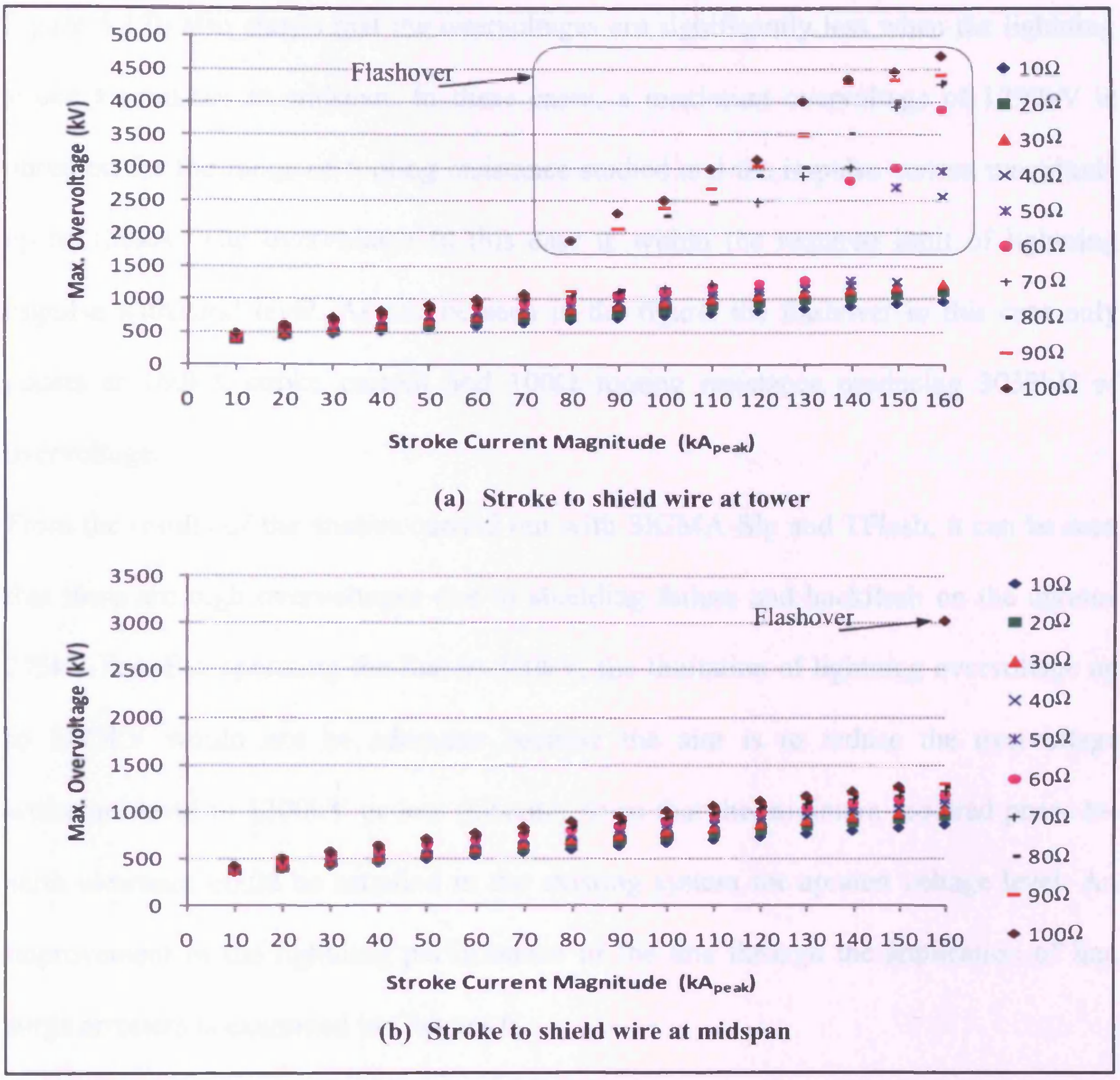


Figure 5.16: Lightning overvoltage waveshape due to shielding failure.

5.7.2 Stroke to Tower Top or Shield Wire on the Uprated L3 Line

The overvoltage magnitude of strokes to towers and shield wire in this case not only depends upon the peak current magnitude, system voltage and insulation strength, it is also influenced by the parameters such as lightning impulse current wave front and the tower footing resistances [5.13, 5.14]. In order to simplify the analysis, the overvoltages are calculated for constant front time of the impulse waveshape in all cases for different tower footing resistances and current magnitudes. However, the impulse front time plays a significant role in determining the lightning strike rate (flashes/100km/year) to the line [5.14]. A 4/77.5 impulse shape is considered for the simulation. Figure 5.17 shows the overvoltage magnitudes for strokes terminating (a) at the tower top and (b) at midspan. The values correspond to a current range of 10kA to 160kA and for different values of tower footing resistance up to 100Ω.

From Figure 5.17, it can be seen that over the range of lighting current and the footing resistance studied, the overvoltage magnitude on the phase conductors due to backflashover can reach 4600kV when the high current lightning wave terminates at the tower top and backflashover occurs in the line. However, the overvoltages do not exceed 1300kV if the footing resistance is limited to 60Ω provided that the stroke currents do not exceed 130kA. This means that the overvoltage magnitude without backflashover does not exceed the lightning impulse withstand level. High values of overvoltages are produced in the line when backflashover occurs as the overvoltage due to lightning surge in the tower is transferred to the line conductors. The overvoltage in this case could be limited by controlling the backflashover in the line. A typical overvoltage shape for a 160 kA, 4/77.5 impulse wave striking shield wire at tower with footing resistance of 80Ω and causing flashover across the line insulators is shown in Figure 5.18.



(a) Stroke to shield wire at tower

(b) Stroke to shield wire at midspan

Figure 5.17: Overvoltage on phase conductors for lightning stroke currents causing backflash.

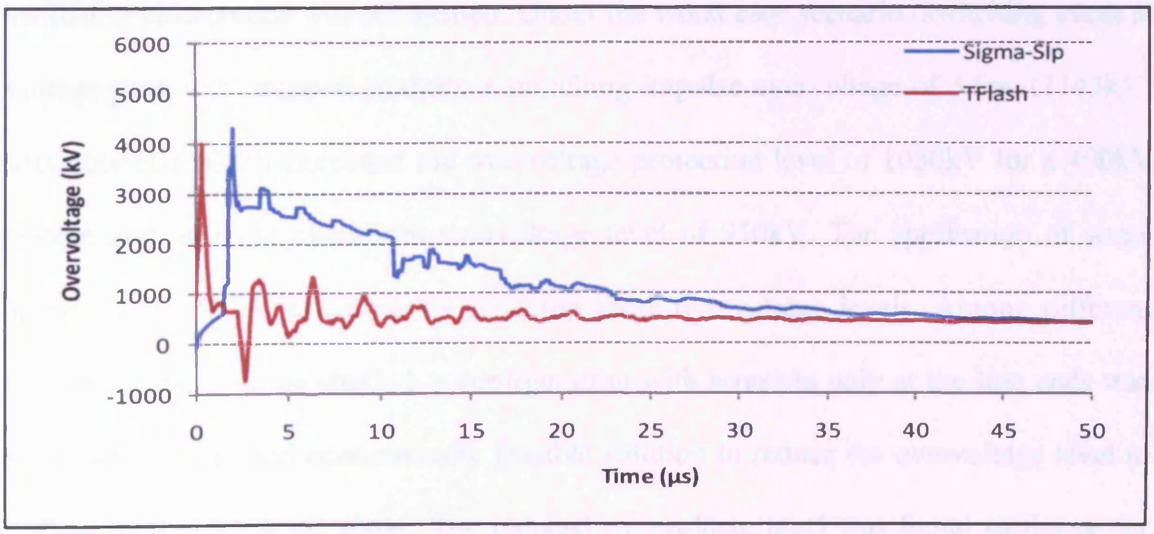


Figure 5.18: Lightning overvoltage waveshape due to backflashover.

Figure 5.17b also shows that the overvoltages are significantly less when the lightning stroke terminates at midspan. In these cases, a maximum overvoltage of 1290kV is observed for the range of footing resistance studied and the impulse current magnitude up to 150kA. The overvoltage in this case is within the required limit of lightning impulse withstand level. As can be seen in the figure, the flashover in this case only occurs at 160kA stroke current and 100Ω footing resistance producing 3033kV of overvoltage.

From the results of the studies carried out with SIGMA-Slp and TFlash, it can be seen that there are high overvoltages due to shielding failure and backflash on the uprated 275kV line. For operating the line to 400kV, the limitation of lightning overvoltage up to 1425kV would not be adequate because the aim is to reduce the overvoltage withstand level to 1300kV or less (Chapter 4) so that the minimum required phase-to-earth clearance could be satisfied in the existing system for uprated voltage level. An improvement in the lightning performance of the line through the application of line surge arresters is examined in Chapter 6.

5.8 CONCLUSIONS

In this chapter, an extensive evaluation of overvoltages produced on an 'L3' line due to switching phenomena was performed. Under the worst case scenario (switching event at voltage peak with trapped charge), a switching impulse overvoltage of 3.5pu (1143kV) was obtained which exceeded the overvoltage protection level of 1050kV for a 400kV system and targeted maximum overvoltage level of 950kV. The application of surge arresters was found effective for reducing these overvoltage levels. Among different arrester configurations studied, a configuration with arresters only at the line ends was found technically and economically feasible solution to reduce the overvoltage level to 2.05pu (669.5kV) at all nodes. The reduced overvoltage level was found sufficient for implementing the targeted switching impulse withstand level of 950kV which requires only 2.2m phase-to-earth clearance for switching overvoltage in 400kV system.

An investigation of lightning overvoltage was performed using two different standard programs: SIGMA-slp and TFlash. The lightning stroke termination statistics obtained using Electrogeometric model showed that only 3% of the total strokes are responsible for the shielding failure and 27% of the stroke result into backflash. In the line studied, it was shown that, almost 100% of the strokes terminating on phase conductors hit the top two phases of the line. An average current magnitude of 22.6kA with a standard deviation of 12.5kA was calculated for strokes causing shielding failure.

The overvoltages due to lightning strikes were computed considering separately the cases of strokes hitting phase conductors and tower top / shield wire. The overvoltage magnitudes for different stroke current magnitudes and shapes showed that the overvoltage due to shielding failure for impulse current more than 6kA exceeds the overvoltage protection level of 1425kV. For a higher value of impulse current which is less likely to hit the phase conductor, this value could reach up to 5000kV. Insulation flashover may occur for impulse current magnitudes above 11kA.

Similarly, when the stroke hits the shield wire or the tower top, the overvoltage magnitude on the conductor was found less than for the shielding failure case. Even though the overvoltage in this case can go up to 4600kV, the value can be limited within the overvoltage protection level for tower footing resistance up to 60Ω for maximum stroke current up to 130kA. It was shown that the overvoltage produced by a stroke terminating on the shield wire at midspan is less than the corresponding magnitude current striking the shield wire at the tower top. In this case, for a tower footing resistance up to 100Ω and a stroke current up to 150kA, the overvoltage magnitudes produced are below the impulse withstand level for a 400kV system.

CHAPTER 6

APPLICATION OF SURGE ARRESTERS FOR LIGHTNING OVERVOLTAGE CONTROL ON UPRATED LINES

6.1 INTRODUCTION

Faults caused by lightning are the main source of line outages especially in the areas with high ground flash density, high earth resistivity and poor shielding. Application of line surge arresters is found to be an efficient tool to control overvoltages due to lightning, thereby, improving the lightning performance of the transmission line. Suitable selection of arrester rating and configuration along the line are crucial for achieving improved reliability of the line.

Line arresters used to control lightning overvoltages are exposed to high magnitude lightning strikes and have to survive high energy discharge duty imposed by the lightning current. In comparison to the substation arrester, the line arrester may experience more energy stress. This is because the incoming surge to a station is limited either by line insulator flashover or by discharge to earth. Therefore, adequate selection of a line arrester also depends upon assessing its energy absorption capability so that it does not fail under conditions of lightning striking either the phase conductor or the shield wire.

In this chapter, optimised lightning overvoltage control by use of surge arresters along the line for voltage uprating is carried out. Overvoltages due to shielding failure and backflash are analysed separately. In Section 5.2.6 (Chapter 5), it is demonstrated that arresters placed only at line ends are sufficient to control switching overvoltages but do not adequately control lightning overvoltages along the line. Unlike switching overvoltages, the control of lightning overvoltage requires closely spaced surge arresters along the line. In order to optimise the number of surge arresters, various arrester installation configurations along the line are studied and compared. A systematic calculation of arrester currents and energy duty is carried out with single stroke cases and also statistically for gapless metal-oxide surge arresters installed on the line.

6.2 SURGE ARRESTER SPECIFICATION

Gapless metal-oxide surge arresters with the following specifications are used [6.1].

Nominal discharge current: 10 kA

Impulse withstand current for 4/10 μs: 100kA

Rated voltage : 360 kV

Maximum Continuous Operating Voltage (MCOV) : 291 kV as per ANSI/IEEE

Energy Capability: 7.8 kJ/kV of rated voltage

The V-I characteristic of the arrester is modelled using the equal area law [6.2] from the data shown in Table 6.1.

Table 6.1: Line surge arrester discharge voltage for impulse currents.

I (kA)	0.5	1	2	5	10	20	40
V (kV)	692	714	742	804	846	931	1046

6.3 LIMITATION OF LIGHTNING OVERVOLTAGE

Using SIGMA-Slp software, an eight span 'L3' line section is selected from the middle of the line and modelled according to the procedure described earlier in Chapter 5 (Section 5.5). Single stroke analysis is performed to estimate the overvoltage level in the line. In this study, SIGMA-Slp is used since it has a tool to perform multiple studies by automatically varying different parameters such as tower footing resistance, ground flash density, insulation level and surge arrester configurations. While in TFlash the study needs to be performed by varying individual parameters one by one which is much time consuming. Apart from this, in the statistical simulations using SIGMA-Slp, the random distribution of lightning stroke parameters and corresponding simulation outputs can be easily traced.

A range of different lightning impulse shapes are used in simulating lightning strikes to the transmission line. In this study, a double exponential, 4/77.5 impulse current wave, as recommended by CIGRE [6.2] and IEEE [6.3], is used. CIGRE and IEEE also recommend specific peak values of lightning current for the different simulations: a peak current magnitude of less than or equal to 20kA under shielding failure scenario and currents above 20kA for backflashover scenarios [6.2, 6.3].

6.3.1 Limitation of Overvoltage due to Shielding Failure

A 20 kA, 4/77.5 lightning impulse was applied to a phase conductor A_1 to simulate shielding failure in the line. Figure 6.1 shows overvoltages calculated for each phase at the struck node. As can be seen in the figure, a maximum overvoltage of 4534kV is calculated at the struck phase; while at non-struck phases, the overvoltages are less than a quarter of this value.

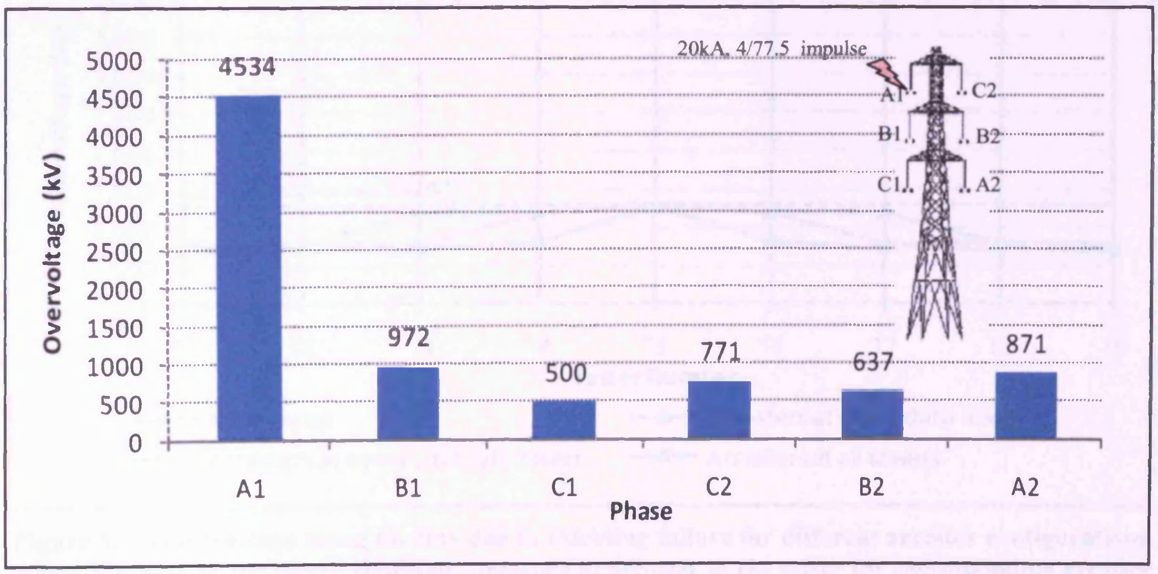


Figure 6.1: Overvoltages produced at different phases due to lightning stroke at phase A1.

The maximum overvoltage on phases at the struck tower and neighbouring towers are calculated with and without surge arresters. Results are compared for three different arrester configurations as given below.

- Arresters at every third tower
- Arresters at every alternate tower
- Arresters at all towers

Figure 6.2 shows the effect of overvoltage control by the use of line surge arresters. As can be seen in the figure, the maximum overvoltage with arresters applied at every third tower or at alternate towers in all phases along the line can significantly reduce the overvoltage due to shielding failure in the line. For all arrester configurations considered, the overvoltages at struck and neighbouring towers are below the targeted lightning impulse withstand level of 1300kV required for uprating the line to 400kV. The maximum overvoltage at the struck node is reduced from 4534kV to 1276.5 kV. At neighbouring towers reduction to 799.5kV and 725.8kV are calculated when arresters

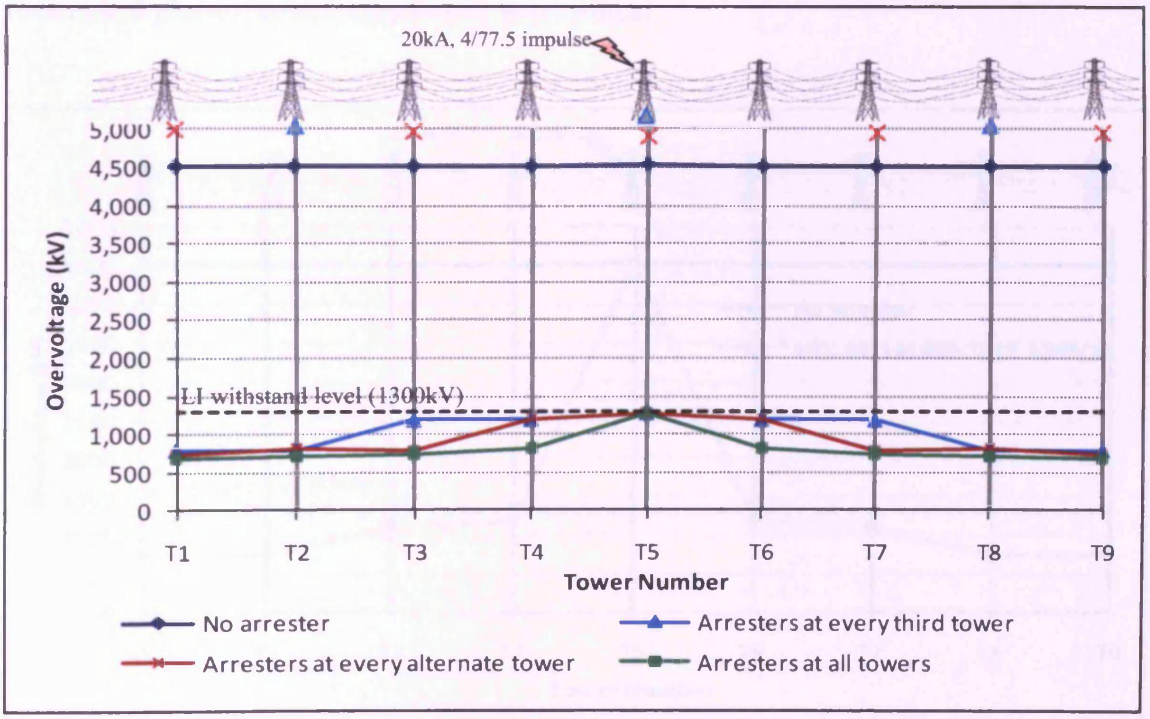


Figure 6.2: Overvoltage along the line due to shielding failure for different arrester configurations. × and ▲ marks in the figure represent presence of arrester in the tower for corresponding arrester configuration indicated.

are placed at every third tower and every alternate tower respectively.

When arresters are placed at all towers, no significant further reduction is obtained. From this initial analysis, as with the switching surge control (Section 5.2.6), the application of surge arresters at every third or alternate tower appears sufficient to achieve the target value of 1300kV lightning impulse withstand level. This allows a reduction in the minimum phase-to-earth clearance requirements from 2.6m to 2.4m for lightning overvoltage.

It is important to note that the result is obtained for the case when lightning strikes the tower at which arresters are installed. However, if lightning strikes at or near to a tower without surge arresters, the arresters at neighbouring towers do not help in reducing overvoltages produced in the struck node as shown in Figure 6.3. With reference to the figure, although neighbouring towers show overvoltages below the impulse withstand level, an overvoltage of 4534kV is obtained at struck node, which is the same value with no surge arresters along the line. This may demand the use of surge arresters in all towers and phases, which may not be economical.

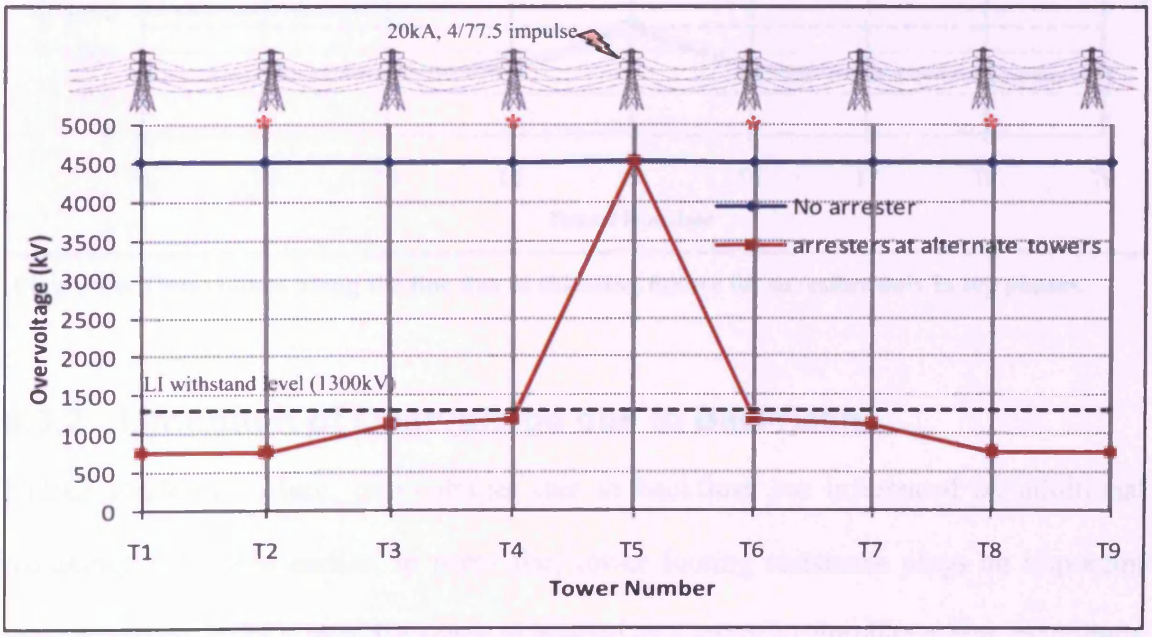


Figure 6.3: Overvoltage along the line due to shielding failure when stroke hits phase conductor near to the tower without surge arrester. * indicate tower with arresters.

With reference to the lightning stroke termination statistics for the line in Section 5.6, it is observed that the shielding failure for this L3 tower design would occur only on the top two phases (A1 and C2). Therefore, if arresters were installed at the top phases only at all towers, this should be sufficient to control overvoltages due to shielding failure. Figure 6.4 shows that lightning overvoltages on the line when arresters are installed at the top phases only are similar to when arresters are installed at all phases, and the values are less than the targeted impulse withstand level of 1300kV. Since the lightning strike hits only the top phase conductors in the low current range, the maximum overvoltage in the striking phase is reduced due to the application of surge arresters.

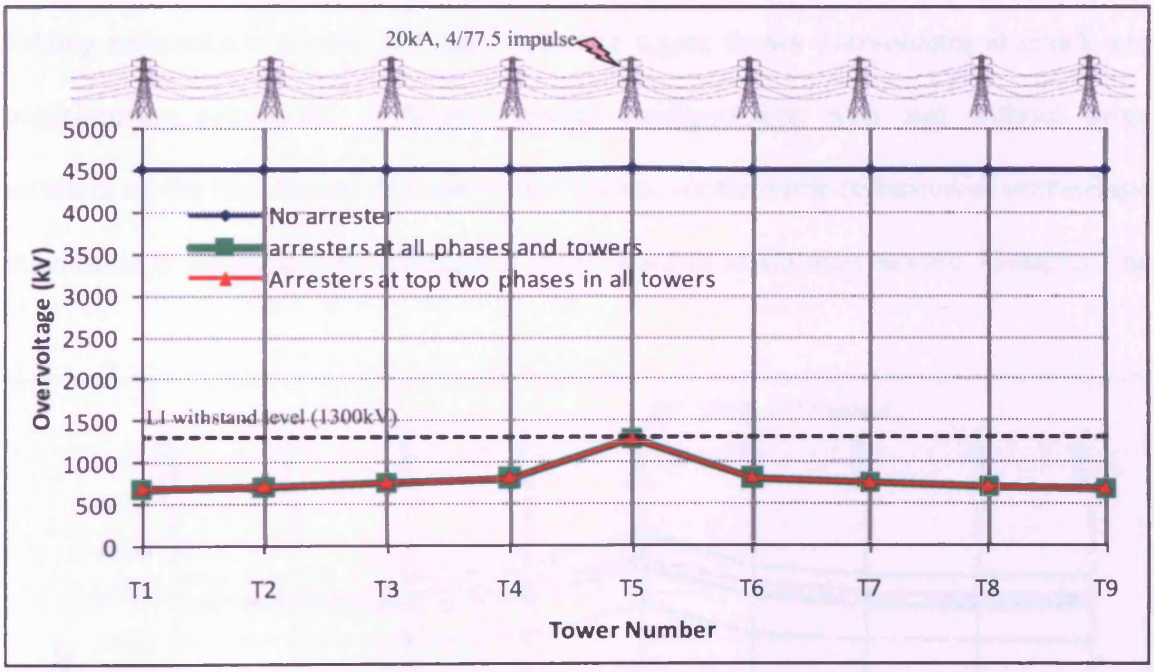


Figure 6.4: Overvoltage along the line due to shielding failure for arresters only in top phases.

6.3.2 Limitation of Overvoltage due to Backflash

Unlike shielding failure, overvoltages due to backflash are influenced by additional parameters. As seen earlier, in particular, tower footing resistance plays an important role. A 160kA, 4/77.5 impulse shape is applied to a tower to simulate a high magnitude impulse that results in a backflashover on the line. The maximum overvoltages produced in the line at struck and neighbouring towers are calculated for different values of tower footing resistance and the results are plotted in Figure 6.5. A maximum overvoltage of 4685kV at the struck tower is obtained for a 100Ω footing resistance. The overvoltages are significantly high above the targeted lightning impulse withstand level (1300kV) for footing resistances greater than or equal to 40Ω, whereas, the value is below the withstand level for footing resistance up to 30Ω. Therefore, for voltage uprating, it is important to control these overvoltages for higher footing resistance values.

The control of overvoltage due to backflashover by use of surge arresters for 80Ω footing resistance is shown in Figure 6.6. The figure shows overvoltages at struck and neighbouring towers for different arrester configurations with and without surge arresters on the line. As can be seen in the figure, considerable reduction of overvoltage magnitude is obtained with arresters at every third or at alternate towers. However, the

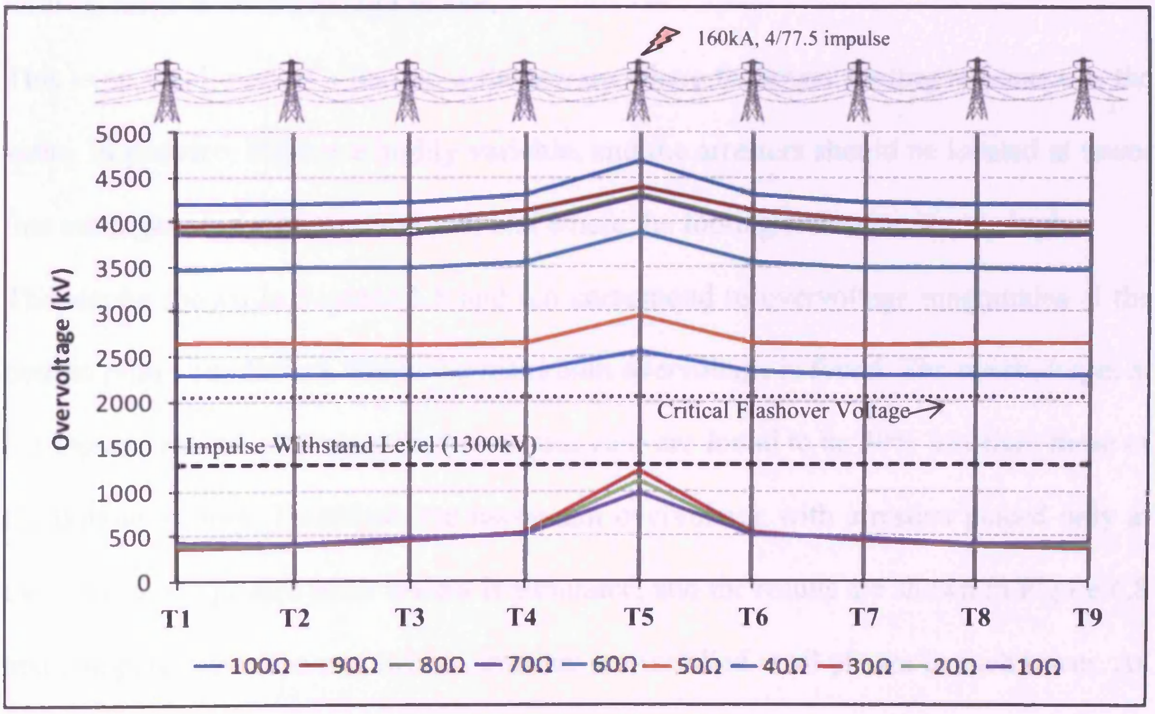


Figure 6.5: Overvoltage along the line due to backflash for different tower footing resistance.

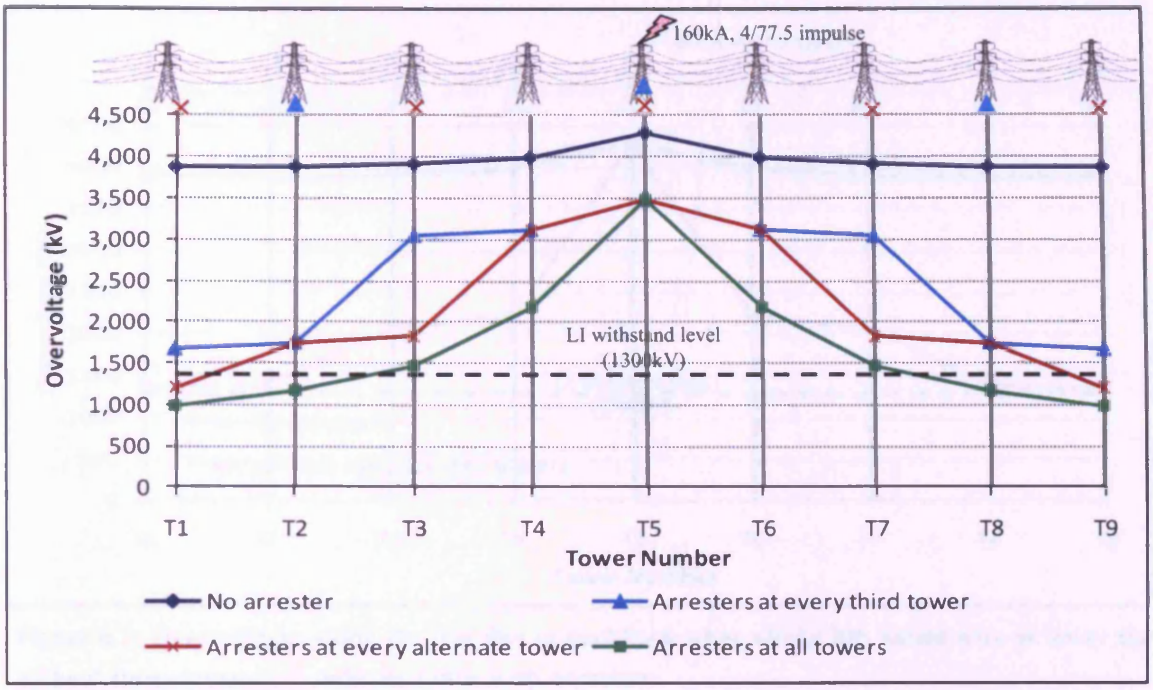


Figure 6.6: Maximum overvoltage along the line due to backflash for different arrester configuration. × and ▲ marks in the figure represent presence of arrester in the tower for corresponding arrester configuration indicated.

overvoltages are not below the targeted withstand level and also these configurations again do not help when the strike hits a tower without surge arrester protection. As presented in Figure 6.7, an overvoltage at a struck tower in this case equals the case with no surge arresters along the line.

This is an ideal case of a line on a flat terrain where the tower footing resistance is the same. In practice, these are highly variable, and the arresters should be located at tower that are higher (or at higher altitude) and where the footing resistance is very high.

The results shown in Figures 6.5 and 6.6 correspond to overvoltage magnitudes at the bottom phase conductors where the maximum overvoltage is found. The overvoltages at the top and middle phase conductors in this case are found to be 50% less than those of the bottom phases. Therefore, the maximum overvoltage with arresters placed only at the bottom two phases in all towers is simulated, and the results are shown in Figure 6.8 and compared with the case where arresters are installed at all phases in each tower. As

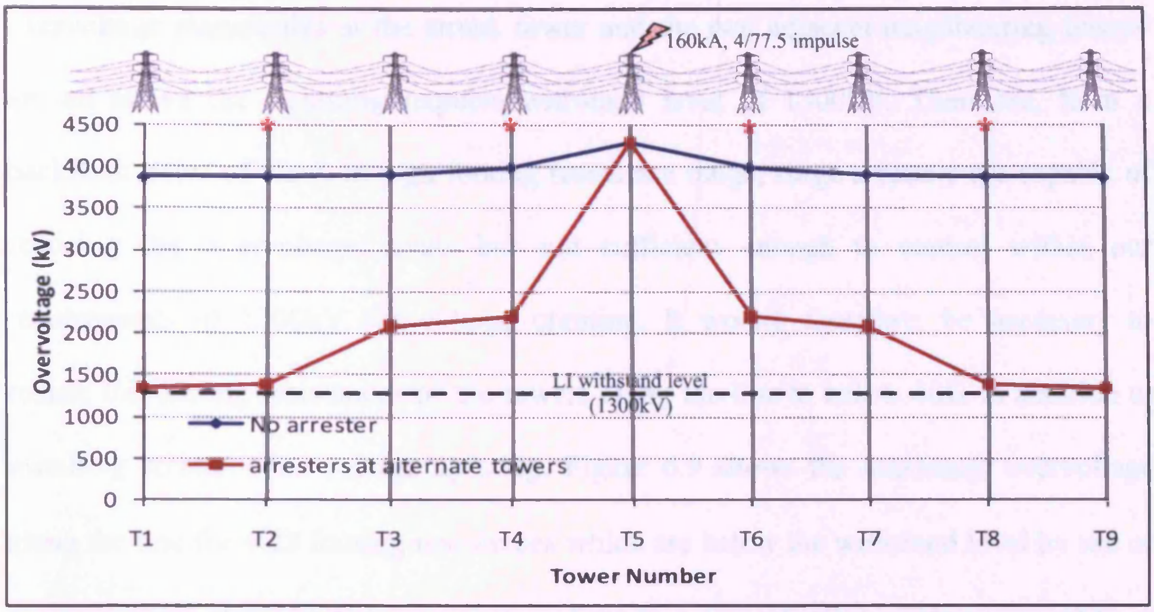


Figure 6.7: Overvoltages along the line due to backflash when stroke hits shield wire at tower top without surge arrester. * indicate tower with arresters.

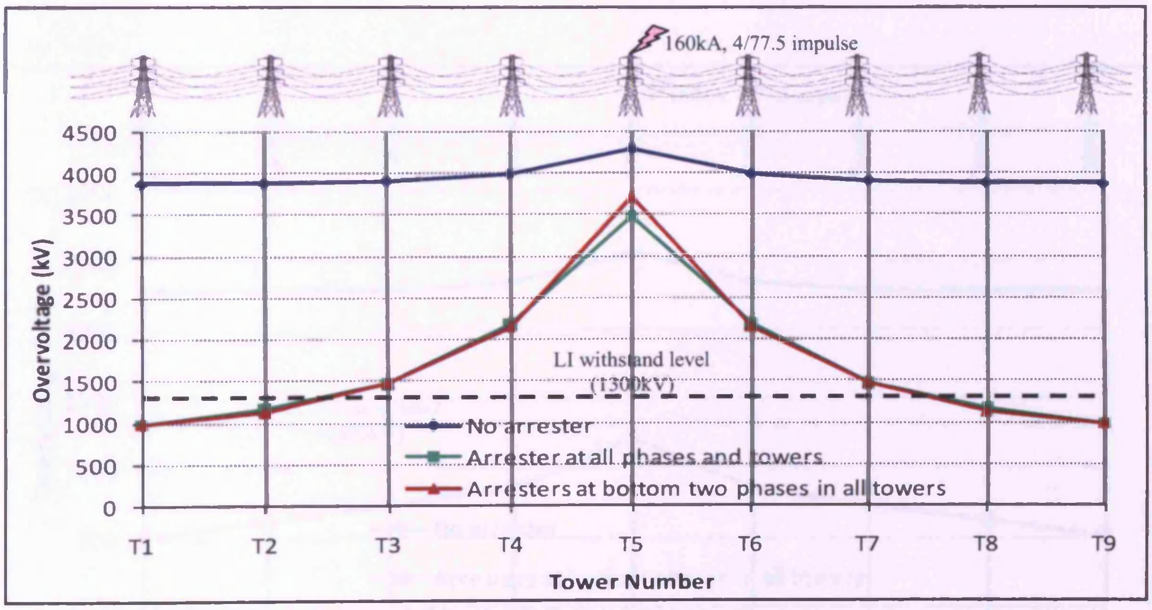


Figure 6.8: Overvoltage along the line due to backflash for arresters only in bottom phases.

seen in the figure, to obtain similar performance as in case of arresters in all phases and towers, it is sufficient to place the arresters in the bottom phases only. However, it is important to note that the controlled overvoltage due to backflashover in all of the results produced so far do not fulfil the requirement of targeted overvoltage level. The overvoltage magnitudes at the struck tower and the two adjacent neighbouring towers are all above the lightning impulse withstand level of 1300kV. Therefore, from a backflash point of view, in high footing resistance range, surge arresters are capable of reducing the overvoltage levels but not sufficient enough to control within our requirements of 1300kV for voltage uprating. It would, therefore, be necessary to reduce the footing resistances of the towers along the line to below 40Ω in addition to installing arresters for voltage uprating. Figure 6.9 shows the maximum overvoltage along the line for 40Ω footing resistances which are below the withstand level by use of surge arresters at the bottom two phases of the line. For a footing resistance equal to or less than 30Ω, there is no need to install surge arresters as the overvoltage values are already below 1300kV.

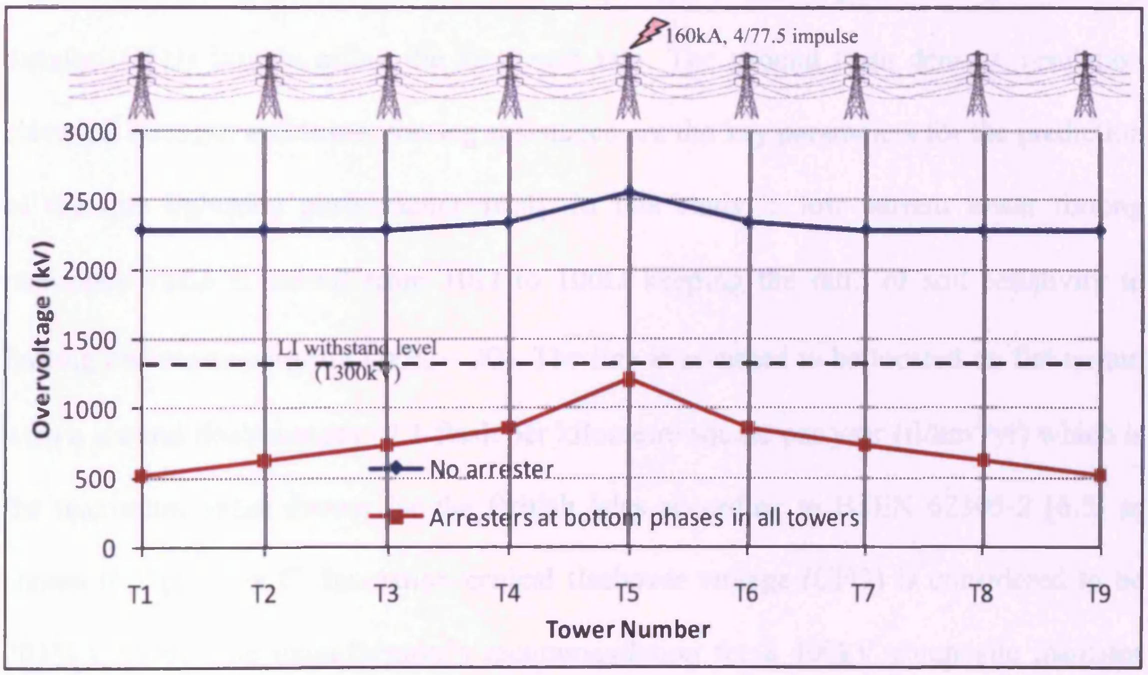


Figure 6.9: Overvoltage along the line due to backflash for tower with 40Ω footing resistance with arresters at bottom phases in all towers.

6.4 LIGHTNING FLASHOVER PERFORMANCE OF THE UPRATED L3 OVERHEAD LINE: STATISTICAL ANALYSIS

Lightning is a major cause of overhead line faults. Between 5% to 10% of the lightning-caused faults are thought to result in permanent damage to power system equipment [6.4]. Together with computation of transient overvoltages, the analysis of lightning performance, therefore, is fundamental when designing new lines and for uprating existing lines to higher voltages. In this section, a statistical stroke analysis is made with different amplitudes of the injected stroke current in order to estimate the flashover performance of the uprated 400kV line. The objective of this study is to estimate the improvement in flashover rate by implementing surge arresters along the line. The investigation is carried out in both Sigma-Slp and TFlash software considering shielding failure and backflashover separately in the line. The parameters such as tower surge impedance, footing resistance, earth resistivity, insulation strength and the ground flash density (GFD) largely affect the flashover rate. The ground flash density, insulation electrical strength and tower footing resistance are the key parameters for the prediction of the line lightning performance [6.4]. In this study, a low current tower footing resistance value is varied from 10Ω to 100Ω keeping the ratio of soil resistivity to footing resistance constant ($\rho/R_0 = 20$). The line is assumed to be located on flat terrain with a ground flash density of 1 flash per kilometre square per year (fl/km^2/yr) which is the maximum value shown for the British Isles according to BSEN 62305-2 [6.5] as shown in Appendix C. Insulation critical flashover voltage (CFO) is considered to be 2035kV as per the manufacturer's recommendation for a 400kV composite insulator [6.6]. An initial study was carried out with line surge arresters positioned at every tower and on every phase conductor. This resulted in a zero flashover rate, but, practically the configuration would be too expensive.

It is understood from the EGM study (Section 5.6), in the low current range, the lightning hits only the top phase conductors of the two circuits during shielding failure. Further, from the overvoltage study, it was established that the maximum overvoltage occurs at bottom phases when the lightning strikes tower top or the shield wire. Considering these two points, the following configurations of arresters, as shown in Figure 6.10 were proposed for the analysis of flashover rate with its application on the line.

The arrester configurations are defined as follows:

N : No arrester

T : Arresters in **T**op phases (A1 and C2) only

M : Arrester in **M**iddle phases (B1 and B2) only

B : Arresters in **B**ottom phases (C1 and A2) only

F : Arrester in **F**our phases (A1, C1, C2 and A2) only

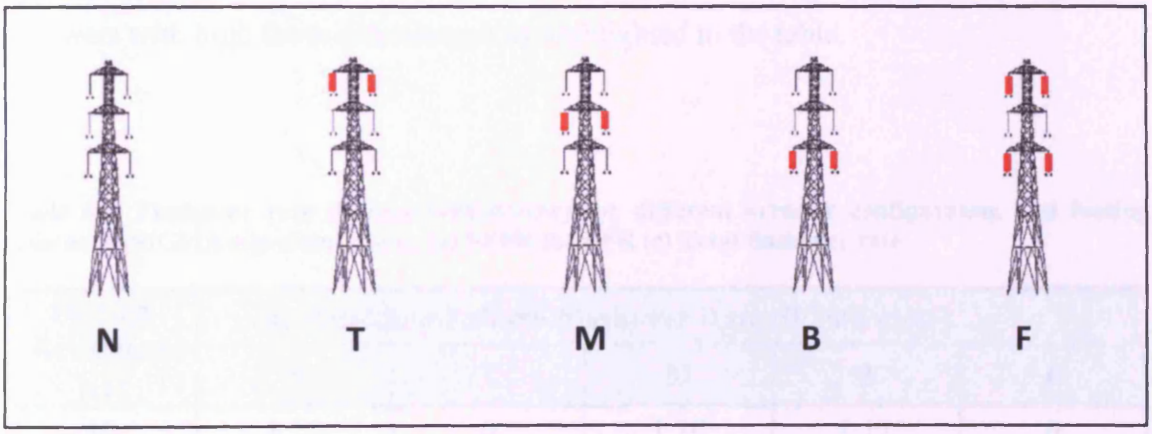


Figure 6.10: Arrester configuration with its code. Red lines indicate arrester in the phase at all towers along the line.

6.4.1 Analysis in SIGMA-Slp

Table 6.2 summarises the results obtained from the SIGMA-Slp simulations. The lightning flashover rates (flashes/100km/year) for different tower footing resistances and under different arrester configurations are shown. A total of 20,000 lightning strokes generated with magnitudes between 1.2kA and 161.1kA and rise time in the range from 1.2μs and 4.38μs are used with the impulse shape varying randomly within 2,000 samples. Fixed tail time of 75μs as standardised in the software is used.

From Table 6.2, it is clear that the applications of surge arresters are a suitable means of protecting the line against lightning flashover. It can be seen that by placing arresters on the top phases only, a zero shielding failure flashover rate (SSFR) is obtained. However, this arrangement can only suppress backflashover under low footing resistance conditions. On the other hand, with arresters installed on the bottom phases only, a zero backflashover rate (BFR) is obtained at the expense of shielding failure. When arresters are installed at the top and bottom phases, both SFFR and BFR can be nullified. The total flashover rate (SFFR + BFR) shown in Table 6.2 suggests that, in order to improve line lightning performance, it is more economical and practical to install arresters only in the top phases at towers with low footing resistance and in the top and bottom phases at towers with high footing resistance as highlighted in the table.

Table 6.2: Flashover rate (flashes/100km/year) for different arrester configuration and footing resistance (SIGMA-Slp simulation). (a) SFFR (b) BFR (c) Total flashover rate

Footing Resistance (Ω)	(a) Shielding Failure Flashover Rate (fl/100km/yr)				
	N	**T**	**M**	**B**	**F**
10	1.12	0	1.10	1.12	0
20	1.12	0	1.10	1.12	0
30	1.12	0	1.10	1.12	0
40	1.12	0	1.10	1.12	0
50	1.12	0	1.10	1.12	0
60	1.12	0	1.10	1.12	0
70	1.12	0	1.10	1.12	0
80	1.12	0	1.10	1.12	0
90	1.12	0	1.10	1.12	0
100	1.12	0	1.10	1.12	0

Footing Resistance (Ω)	(b) Backflashover Rate (fl/100km/yr)				
	N	T	M	B	F
10	0	0	0	0	0
20	0	0	0	0	0
30	0	0	0	0	0
40	0	0	0	0	0
50	0.03	0	0	0	0
60	0.08	0.01	0	0	0
70	0.12	0.04	0	0	0
80	0.21	0.06	0	0	0
90	0.30	0.09	0.04	0	0
100	0.44	0.12	0.05	0	0
Footing Resistance (Ω)	**(c) Total Flashover Rate (fl/100km/yr)**				
	N	**T**	**M**	**B**	**F**
10	1.12	0	1.10	1.12	0
20	1.12	0	1.10	1.12	0
30	1.12	0	1.10	1.12	0
40	1.12	0	1.10	1.12	0
50	1.15	0	1.10	1.12	0
60	1.20	0.01	1.10	1.12	0
70	1.24	0.04	1.10	1.12	0
80	1.33	0.06	1.10	1.12	0
90	1.42	0.09	1.14	1.12	0
100	1.56	0.12	1.15	1.12	0

6.4.2 Analysis in TFlash

Table 6.3 shows the results obtained from TFlash simulations. Here, the simulations were carried out with 32 different stroke current range between 2.5kA and 160kA. The results in this case again confirm the same findings described under SIGMA-Slp simulations. The magnitude of flashover rate is slightly higher than that obtained in SIGMA-Slp. It is because of the difference in statistical simulation method adopted by the software as explained earlier in Section 5.6.

Table 6.3: Flashover rate (flashes/100km/year) for different arrester configuration and footing resistance (TFlash simulation). (a) SFFR (b) BFR (c) Total flashover rate

Footing Resistance (Ω)	(a) Shielding Failure Flashover Rate (fl/100km/yr)				
	N	**T**	**M**	**B**	**F**
10	1.43	0	1.21	1.43	0
20	1.43	0	1.21	1.43	0
30	1.43	0	1.21	1.43	0
40	1.43	0	1.21	1.43	0
50	1.43	0	1.21	1.43	0
60	1.43	0	1.21	1.43	0
70	1.43	0	1.21	1.43	0
80	1.43	0	1.21	1.43	0
90	1.43	0	1.21	1.43	0
100	1.43	0	1.21	1.43	0

Footing Resistance (Ω)	(b) Backflashover Rate (fl/100km/yr)				
	N	**T**	**M**	**B**	**F**
10	0	0	0	0	0
20	0	0	0	0	0
30	0	0	0	0	0
40	0	0	0	0	0
50	0.03	0	0	0	0
60	0.08	0	0	0	0
70	0.15	0.02	0	0	0
80	0.26	0.04	0	0	0
90	0.34	0.06	0	0	0
100	0.48	0.09	0.02	0	0

Footing Resistance (Ω)	(c) Total Flashover Rate (fl/100km/yr)				
	N	**T**	**M**	**B**	**F**
10	1.43	0	1.21	1.43	0
20	1.43	0	1.21	1.43	0
30	1.43	0	1.21	1.43	0
40	1.43	0	1.21	1.43	0
50	1.46	0	1.21	1.43	0
60	1.51	0	1.21	1.43	0
70	1.58	0.02	1.21	1.43	0
80	1.69	0.04	1.21	1.43	0
90	1.77	0.06	1.21	1.43	0
100	1.91	0.09	1.23	1.43	0

6.5 ENERGY STRESS ON SURGE ARRESTERS

Based on the lightning performance analysis carried out in previous sections, the maximum energy absorbed by a line surge arrester can be calculated using the product of voltage and current traces computed by a travelling wave simulation technique as described in [6.7]. In this investigation, the insulator flashover is neglected since the voltage measured across the line insulator which is protected by the surge arrester is found to be much lower than the CFO of the insulator string even under high magnitude lightning strike. Therefore, it is assumed that the insulators do not flashover when protected by a surge arrester.

In this study, a double exponential, 4/77.5 impulse current wave is used. In order to evaluate the maximum energy absorbed by surge arresters, unless otherwise specified, a 20kA lightning stroke hitting the phase conductor A1 is used for the shielding failure case and a 160kA stroke hitting the tower-top was used in the backflashover case.

6.5.1 Distribution of Energy Stress

Figure 6.11 shows the energy stress distribution in surge arresters installed in all phases in the case when a lightning strike hits a phase conductor or a shield wire. Dots (•) in the figures represent the presence of arrester in that particular phase. When a low current lightning hits a phase conductor, the energy absorbed by arresters at any tower is different. As expected, the arrester installed on a stricken phase absorbs the highest energy compared with arresters on other phases. However, when high current lightning hits the shield wire, it is shown that any two arresters installed at the same height absorb equal energy. Also, the arresters installed on the bottom two conductors absorb more energy than the arresters installed on the four conductors above.

In Section 6.4, it is shown that the top phase conductors are more vulnerable to shielding failure while those at the bottom phases are more vulnerable to backflashover.

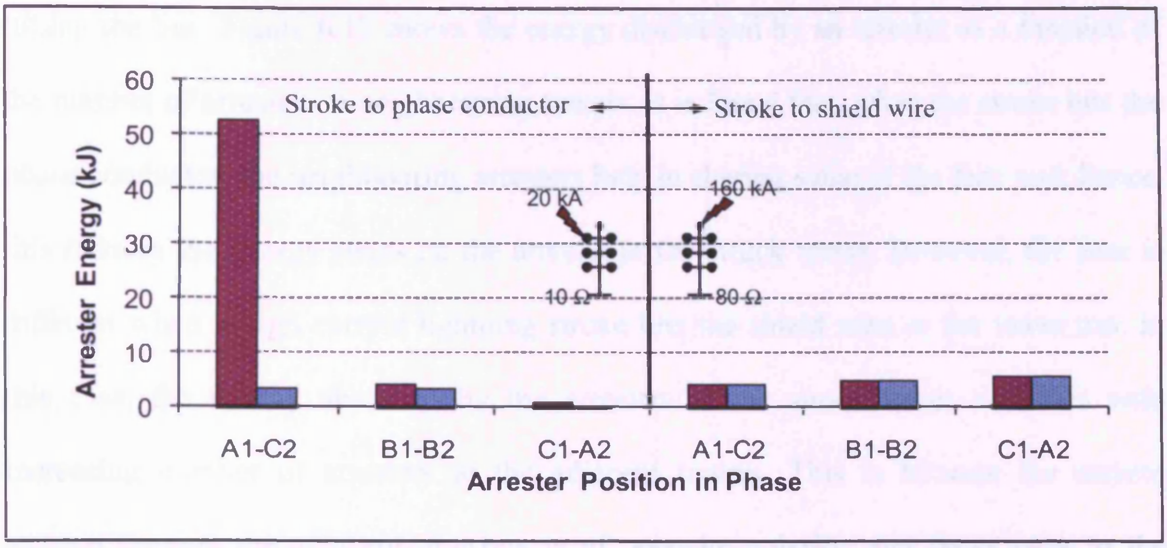


Figure 6.11: Distribution of energy stress in surge arresters installed at a stricken tower.

As shown in Figure 6.11, arrester energy requirement can be such that the top arresters are more likely to experience direct strikes of lower magnitudes while the lower ones can be subjected to stresses equivalent to those causing backflashover.

6.5.2 Parametric Analysis

Appropriate selection of an arrester as a function of its energy stress depends upon a number of parameters. These parameters can be classified as line parameters and lightning stroke parameters. Parameters such as arresters in neighbouring towers, tower footing resistance and angle of power frequency voltage are considered as line parameters whereas stroke peak current magnitude, front time and tail time are considered as lightning stroke parameters. The single stroke analysis is carried out to understand the effect of these parameters for both the case of stroke hitting a phase conductor and the shield wire.

6.5.2.1 Influence of Arresters in Neighbouring Towers

In practice, the energy shared by arresters at a tower is influenced by the presence of arresters at neighbouring towers. The nature of influence of these adjacent arresters on the "struck" arrester's energy stress depends upon the position of the lightning stroke hitting the line. Figure 6.12 shows the energy discharged by an arrester as a function of the number of arresters at neighbouring towers. It is found that, when the stroke hits the phase conductor, the neighbouring arresters help in sharing some of the duty and, hence, this reduces the energy stress on the arrester at the struck tower. However, the case is different when a high current lightning stroke hits the shield wire or the tower top. In this case, the energy absorbed by the arresters at the struck tower increases with increasing number of arresters at the adjacent towers. This is because the current passing through the adjacent arresters is of opposite polarity, and flows back to the striking point resulting into the increase of energy absorbed by the arrester at the struck tower.

Figure 6.13 shows the energy shared by arresters at neighbouring towers, when lightning strikes a phase conductor or a shield wire. It can be said that when lightning hits the phase conductor, the neighbouring arresters share significant energy thereby reducing the stress of the arresters at stricken tower. Compared to the stress of the arrester at stricken tower (91.2kJ), the stress of the arrester at immediate adjacent tower is more than 75% (68.6kJ). This value decreases slowly as the distance increases. The

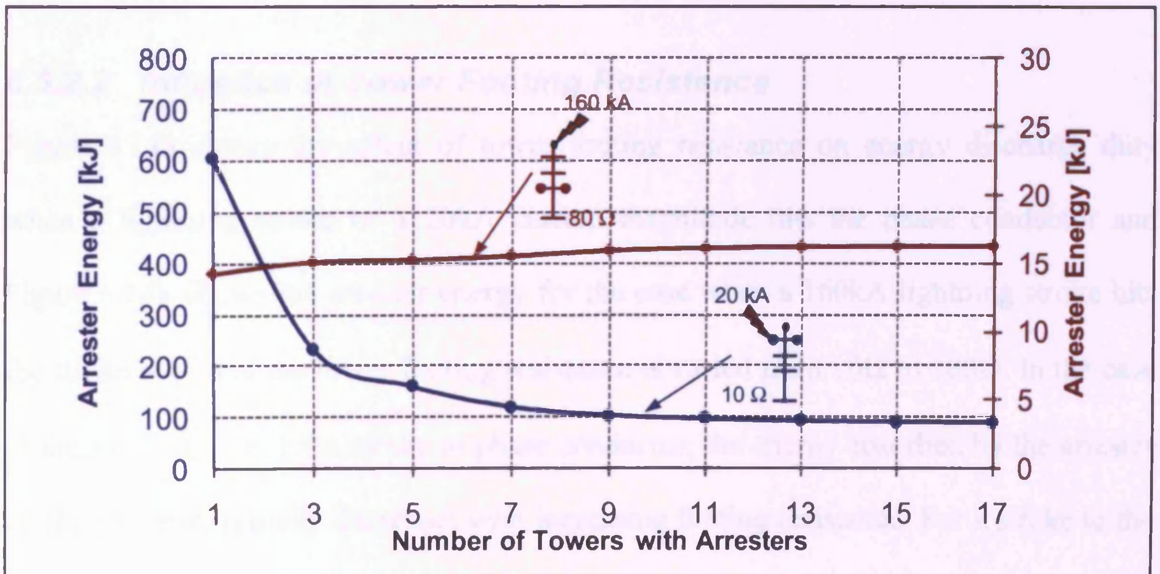


Figure 6.12: Arrester energy as a function of number of arresters at adjacent towers.

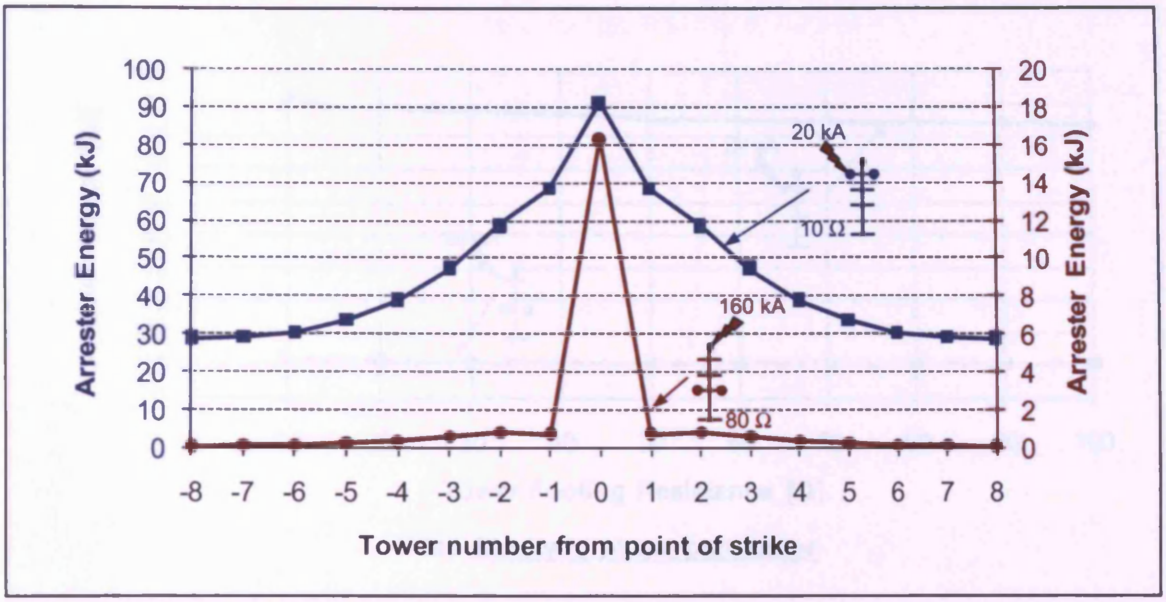


Figure 6.13: Energy shared by arresters at neighbouring towers. Tower 0 is the struck tower.

arrester installed at a tower located at eight spans away from the stricken arrester absorbs an energy of 28.9kJ. Conversely, when lightning hits the shield wire, the arresters in the stricken tower is highly stressed and the stresses at neighbouring arresters are almost negligible. In this case, an arrester at a stricken tower absorbs 16.33kJ of energy whereas stress at the immediate adjacent arrester is only 0.74 kJ. Arresters at the far ends (8-spans away) do not play any significant role as the arresters absorb negligible energy (0.07 kJ).

6.5.2.2 Influence of Tower Footing Resistance

Figure 6.14a shows the effect of tower footing resistance on energy discharge duty when a lightning stroke of a 20kA current magnitude hits the phase conductor and Figure 6.14b shows the arrester energy for the case when a 160kA lightning stroke hits the shield wire and the tower footing resistance is varied from 10Ω to 100Ω. In the case of the shielded line, for a stroke to phase conductor, the energy absorbed by the arrester on the phase marginally decreases with increasing footing resistance. For a stroke to the shield wire, however, a high value of footing resistance increases the arrester energy

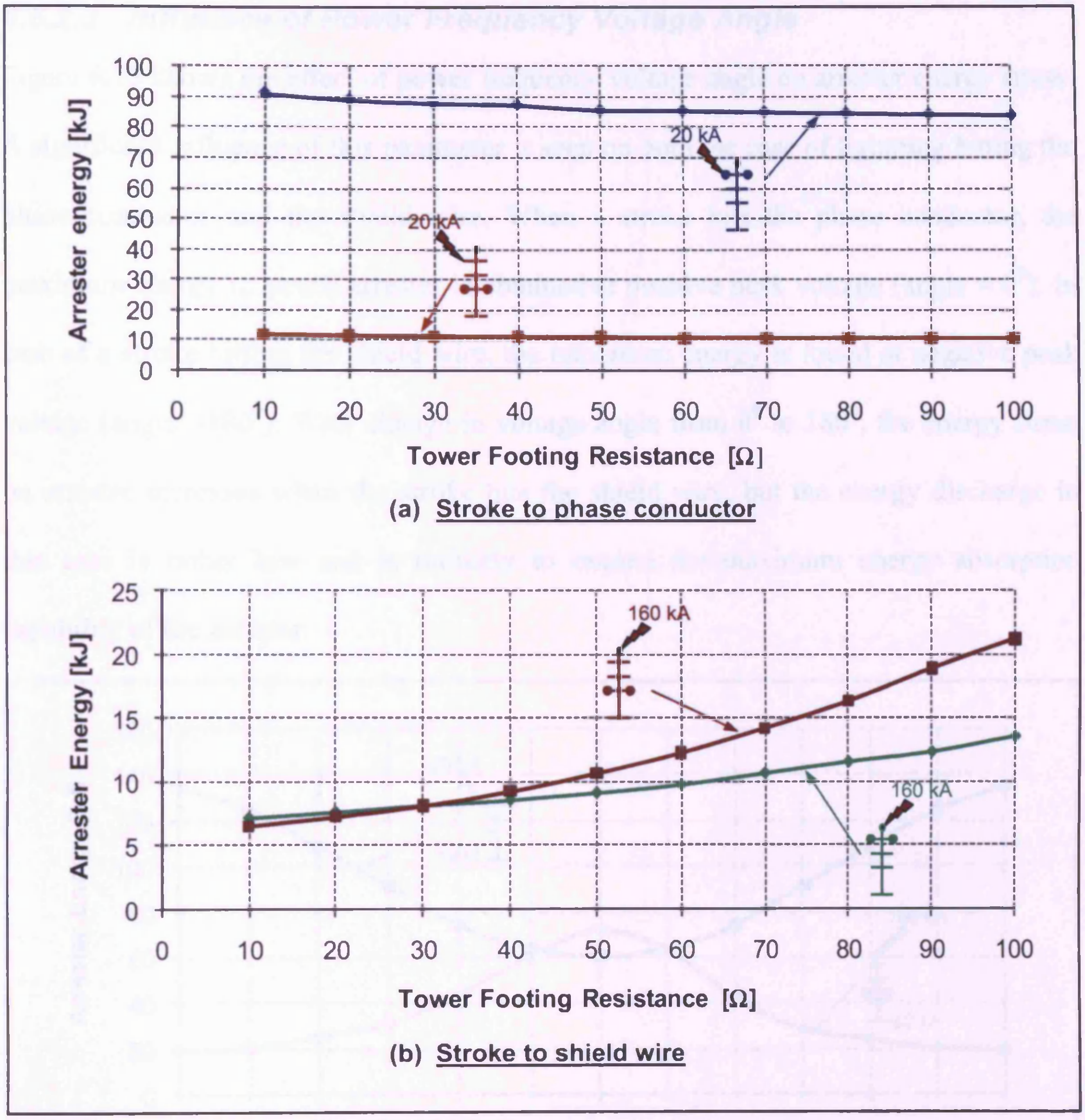


Figure 6.14: Arrester energy dependence on tower footing resistance.

discharge. Arresters installed on the top phases are more stressed with low tower footing resistance value whereas bottom phase arresters are more stressed in the case of high footing resistance value. The result assumes no flashover on the phase conductor without surge arrester protection. However, in case of flashover, a high value of stroke current is discharged through a flashover path creating less stress to arresters installed at other phases.

6.5.2.3 *Influence of Power Frequency Voltage Angle*

Figure 6.15 shows the effect of power frequency voltage angle on arrester energy stress. A significant influence of this parameter is seen on both the case of lightning hitting the phase conductor and the shield wire. When a stroke hits the phase conductor, the maximum energy in struck arrester is obtained at positive peak voltage (angle = 0^0). In case of a stroke hitting the shield wire, the maximum energy is found at negative peak voltage (angle =180^0). With change in voltage angle from 0^0 to 180^0, the energy stress on arrester increases when the stroke hits the shield wire, but the energy discharge in this case is rather low and is unlikely to exceed the maximum energy absorption capability of the arrester.

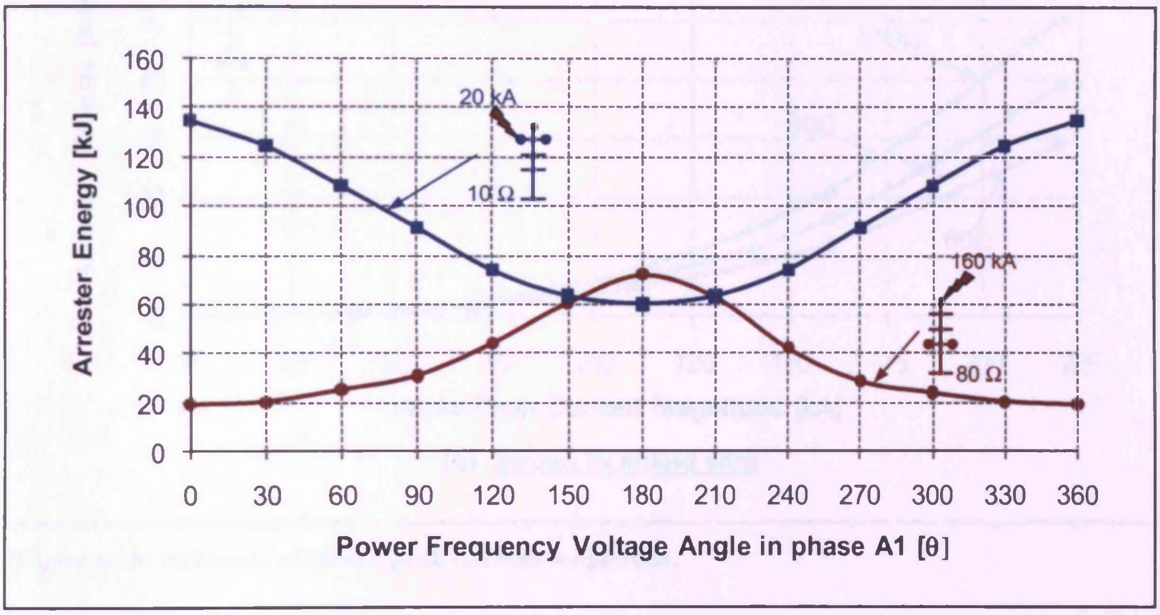
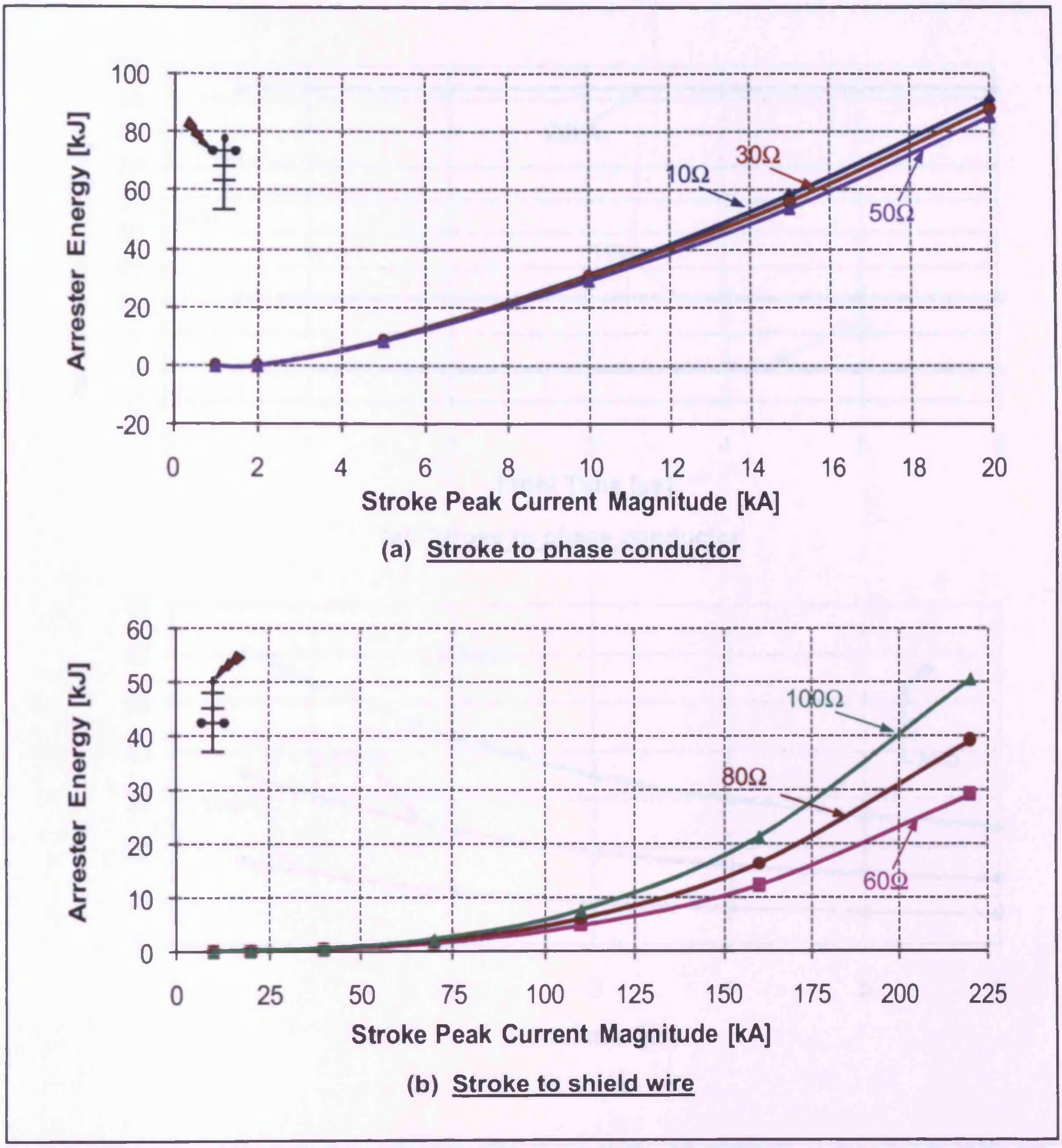


Figure 6.15: Arrester energy dependence on power frequency voltage angle at lightning strike.

6.5.2.4 *Influence of Stroke Peak Current Magnitude*

Figure 6.16 shows the effect of stroke peak current magnitude on arrester energy. This effect is examined for different tower footing resistances. The energy absorbed by the arrester increases non-linearly with increasing peak current magnitude, and this is obtained for all cases of impact point and tower footing resistance.



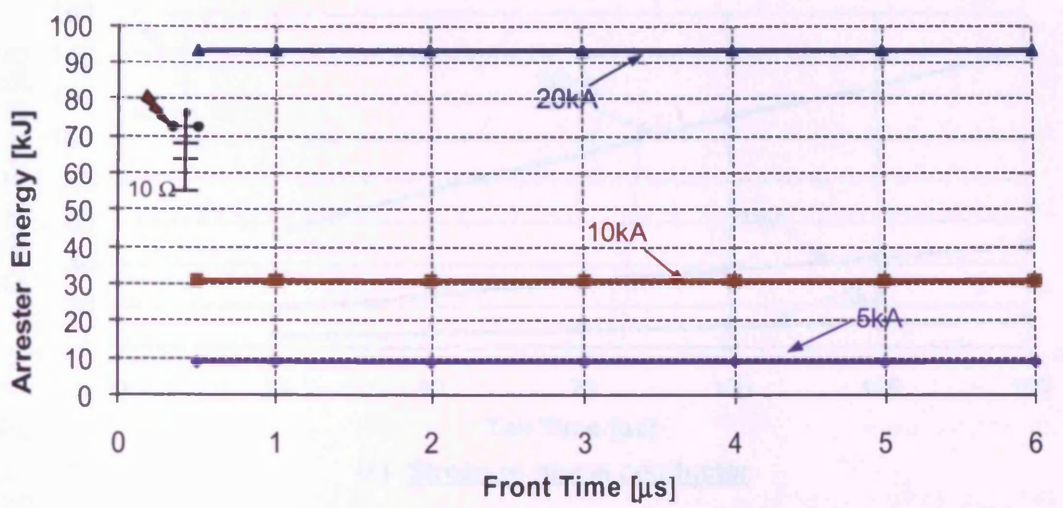
(a) Stroke to phase conductor

(b) Stroke to shield wire

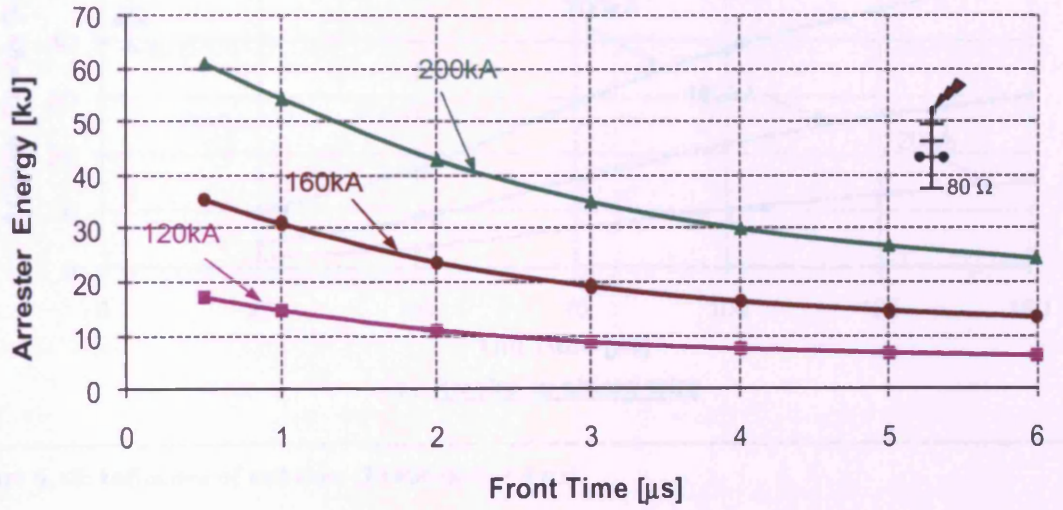
Figure 6.16: Influence of stroke peak current magnitude.

6.5.2.5 Influence of Stroke Front Time

The effect of impulse front time for different stroke peak current magnitudes is shown in Figure 6.17. In the case of lightning hitting the phase conductor, the change in front time does not have any influence on the arrester energy. However, the arresters are less stressed with slower front time when lightning hits the shield wire.



(a) Stroke to phase conductor



(b) Stroke to shield wire

Figure 6.17: Influence of front time (Tail time = 77.5 μs).

6.5.2.6 *Influence of Stroke Tail Time*

Unlike front time, the stroke current tail time has a significant influence on the energy absorbed by line arresters as shown in Figure 6.18. The arrester energy increases with increasing tail time of the lightning impulse.

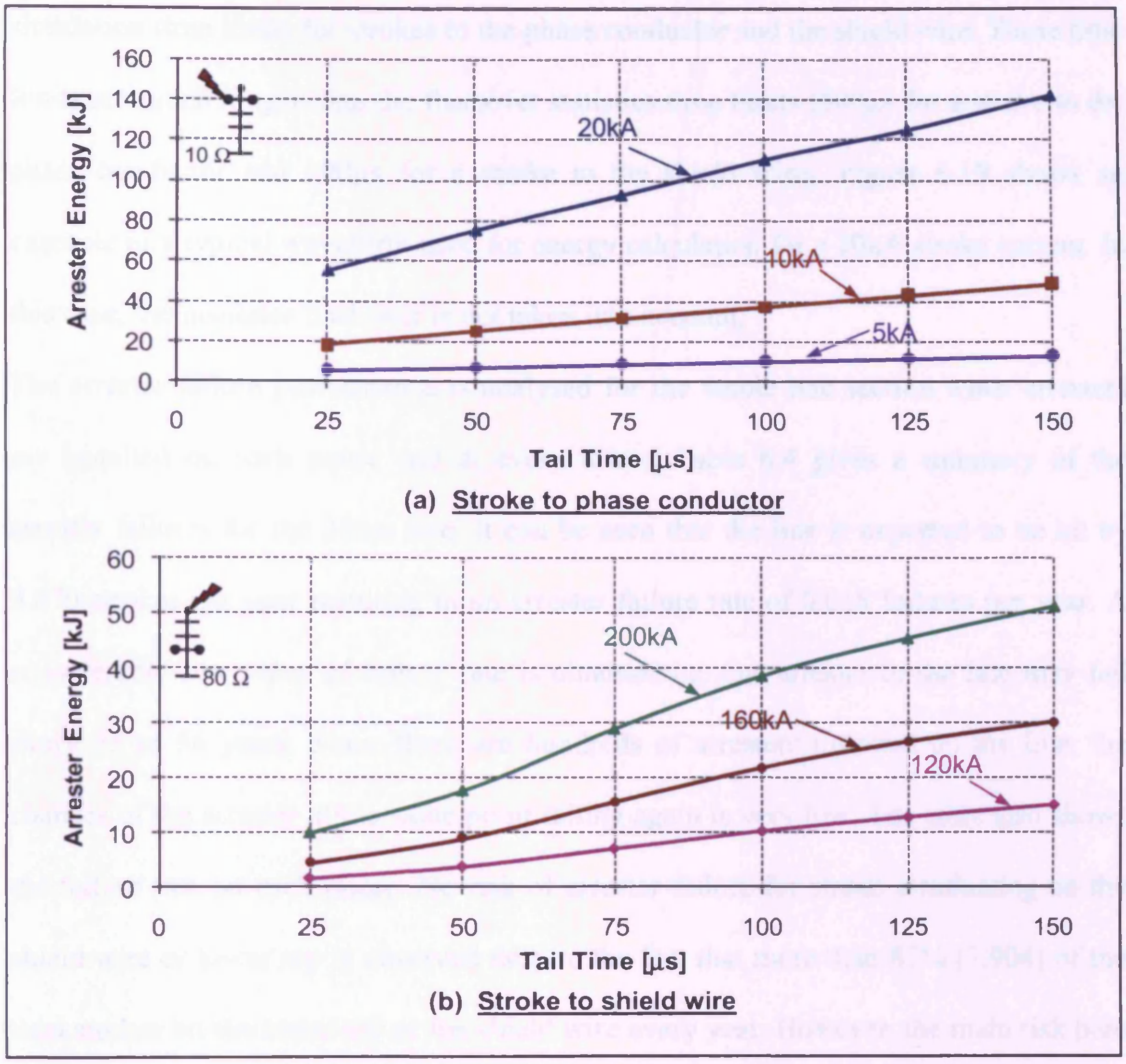


Figure 6.18: Influence of tail time (Front time = 4 µs).

6.6 ARRESTER FAILURE PERFORMANCE

In order to estimate the failure rate of arresters due to excessive energy absorption and to guarantee that the arresters installed on the line have sufficient energy capability to withstand lightning strikes to the phase conductors or to the shield wire, a detailed investigation was carried out. To determine the arrester failure probability, the integrated energy for each arrester is calculated and compared with the failure probability curve from EPRI report 1000461 [6.8].

The statistical simulation method is used. To integrate the energy through the arresters over most of the stroke duration, the method used in TFlash software adopts different simulation time limits for strokes to the phase conductor and the shield wire. These time limits are much longer than the flashover statistics time limits (500μs for a stroke to the phase conductor and 100μs for a stroke to the shield wire). Figure 6.19 shows an example of a typical waveform used for energy calculation for a 20kA stroke current. In this case, the insulator flashover is not taken into account.

The arrester failure performance is analysed for the whole line section when arresters are installed on each phase and at every tower. Table 6.4 gives a summary of the arrester failures for the 35km line. It can be seen that the line is expected to be hit by 9.070 strokes per year resulting in an arrester failure rate of 0.018 failures per year. A considerably low value of failure rate is obtained i.e. one arrester in the line may fail every 55 to 56 years. Since there are hundreds of arresters installed on the line, the chances of the arrester at the same point failing again is very low. The table also shows the failure rate on each phase. No risk of arrester failure for stroke terminating on the shield wire or tower top is observed despite the fact that more than 87% (7.904) of the total strokes hit the tower top or the shield wire every year. However, the main risk here is associated with the arresters at the top phase (installed on phases A1 and C2) with direct strokes terminating on the phase.

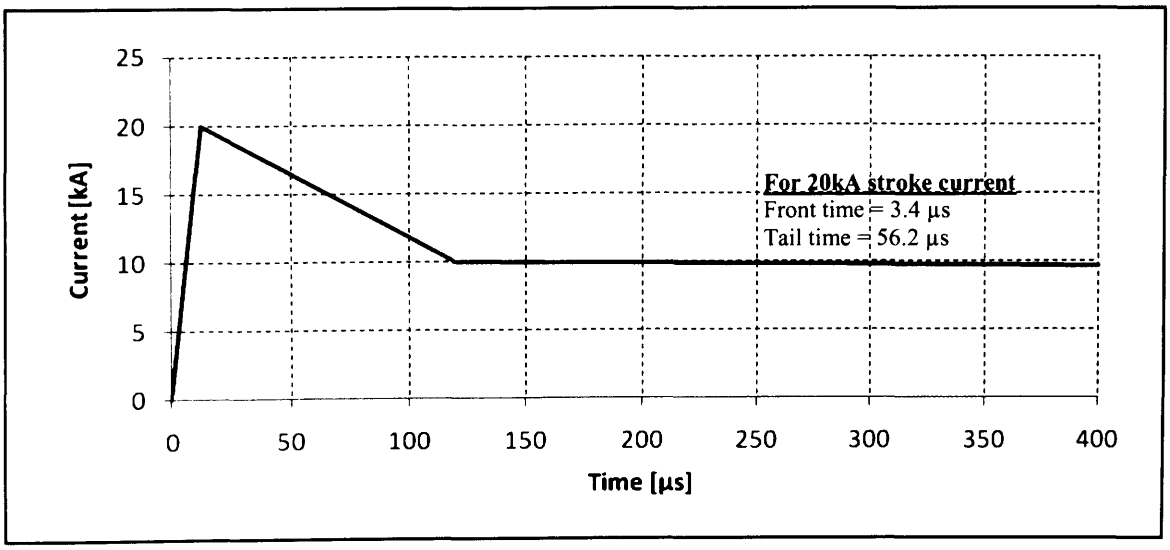


Figure 6.19: A typical equal probability waveform (20kA stroke current).

Table 6.4: Arrester failure performance of the 35km long L3 line.

Direct strikes per year = 9.070 (Total) Arrester failure per year = 0.018 Direct strikes per year = 1.166 (phase) Direct strikes per year = 7.904 (shield wire & tower top)				
Arrester Failure by Phase				
Phase	Direct Strikes Per Year	Failure From		
		Shield Strike	Phase Strikes	All Strikes
A1	0.576	0	0.009	0.009
B1	0.007	0	0	0
C1	0	0	0	0
C2	0.576	0	0.009	0.009
B2	0.007	0	0	0
A2	0	0	0	0

Figure 6.20 shows the arrester failure rate at each tower along a section of the line. The failure rate in an individual tower is very low. A tower with a failure rate of 0.001 per year means an arrester at that particular tower fails every 1000 years. Therefore, the arresters considered in this study can operate at low risk of failure. This of course depends on the appropriate selection of the arresters.

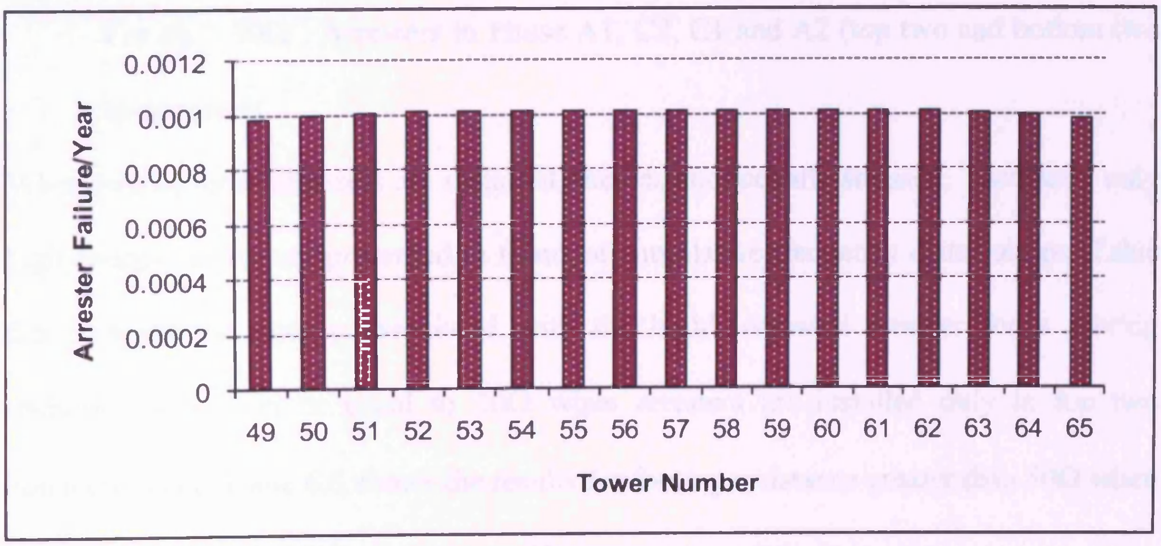


Figure 6.20: Arrester failure rate at each tower along a section of the line.

6.7 CUMULATIVE FREQUENCY DISTRIBUTION OF ARRESTER ENERGY

Energy duties are computed statistically with 2,000 simulations for selected arrester configurations, and the results are presented in the form of cumulative frequency distribution of arrester energy.

The parametric analysis carried out in Section 6.5 showed that the energy stress on the line arresters mainly depends upon the two important parameters of the lightning stroke: peak value of the lightning current and tail time. The probability distribution of arrester energy, therefore, is a function of probability density function of the peak lightning current and probability density function of the tail time [6.9, 6.10]. In this study, two-line CIGRE distribution [6.2] is used to represent stroke peak current distribution. Stroke current with 77.5 μs of tail time (median value with standard deviation 0.577) is used. The arrester energy also depends upon the tower footing resistance (R_{ft}) value. Since the arresters in the top two conductors only are sufficient for line section with low footing resistance and arresters in four conductors (top two and bottom two) only are sufficient for high footing resistance section, the following strategy for installation of arresters is used:

- For $R_{ft} \leq 50\Omega$: Arresters in phase A1 and C2 (top two conductors)
- For $R_{ft} > 50\Omega$: Arresters in Phase A1, C2, C1 and A2 (top two and bottom two conductors)

When two or more arresters are installed, they are not equally stressed. Therefore, only high energy values are presented in terms of cumulative frequency distributions. Table 6.5 presents the energy associated with the highly stressed arrester for a footing resistance less than or equal to 50Ω when arresters are installed only in top two conductors and Table 6.6 shows the results for footing resistance greater than 50Ω when arresters are installed in the top two and bottom two conductors.

Table 6.5: Arrester Energy (kJ) in terms of cumulative frequency distribution for different tower footing resistance values – Arresters in top two phases (A1 and C2)

Probability → / Footing Resistance ↓	10%	5%	2%	1%	0.5%	0.1%
10Ω	0.04	02.9	191.3	307.7	449.8	683.2
20Ω	0.73	56.5	208.5	321.1	429.5	908.7
30Ω	0.17	11.4	125.2	222.6	308.1	818.4
40Ω	1.94	30.5	165.6	258.4	414.1	641.3
50Ω	2.84	29.5	168.9	262.9	434.4	746.7

Table 6.6: Arrester Energy (kJ) in terms of cumulative frequency distribution for different tower footing resistance values – Arresters in top two and bottom two phases (A1, C2, C1 and A2)

Probability → / Footing Resistance ↓	10%	5%	2%	1%	0.5%	0.1%
60Ω	0.27	23.3	173.2	284.3	424.7	897.2
70Ω	1.10	20.0	127.8	206.5	285.8	593.4
80Ω	3.20	54.8	172.7	244.9	340.5	700.2
90Ω	1.86	36.8	138.9	266.2	335.3	852.4
100Ω	4.25	19.0	160.3	258.8	365.1	477.8

In both cases, there is only 0.1% probability to exceed an arrester energy duty of 600kJ. A maximum energy of 908.7 kJ is recorded in Table 6.5 which is far below the arrester energy capability of 2808 kJ. According to the EGM result shown in Table 5.4 (Chapter 5), the line under study collects 11.3 strokes per year. Therefore, the probability of this occurrence is only once in 88.5 years. Tables 6.5 and 6.6 show that the arresters are not highly stressed even when they are installed on the bottom phase conductors. As can be seen, in both cases, only 1% of the arrester energy is likely to exceed 10% of the arrester energy capability. Here, a line arrester was chosen with a discharge class 3 as per IEC 60099-4 [6.11] and an energy capability of 7.8 kJ/kV of rated voltage. The analysis of energy duty shows that the arresters with lower voltage rating with line discharge class 2 could also be installed to achieve the required protection level in the line.

6.8 Conclusions

In this chapter, the application of surge arresters for control of lightning overvoltages was investigated. It was demonstrated that the application of line surge arresters can effectively control overvoltages due to lightning impulse, thereby, reducing the minimum phase-to-earth clearance requirements. Detailed analysis of developed overvoltages under direct strikes and backflashovers helped to optimise and reduce the number of surge arrester to be deployed along the line. It was shown that installing arresters at the top phases only is sufficient to control overvoltage due to shielding failure below the targeted value of lightning withstand of 1300kV. However, with this solution, the control of overvoltages due to backflashover is not always offered for high footing resistance of the towers. The results for backflashover showed that the overvoltages at the struck tower and adjacent neighbouring towers are not reduced to a significant level such that the targeted withstand level could be chosen to reduce the minimum required phase-to-earth clearance in the uprated line. It was concluded that from the backflashover point of view, voltage uprating by use of surge arrester is only possible for lines with low values of tower footing resistances (up to 40Ω). The minimum required clearance of a line with high tower footing resistances can only be minimised using surge arresters if there is possibility of reducing the footing resistances to a value equal to or less than 40Ω.

The lightning flashover performance analysis of the proposed uprated L3 line showed that the arrester combination suitable for controlling lightning overvoltage is sufficient for improving the lightning performance of the line. It was shown that, installing line arresters on the top phases only improves shielding failure flashover rate, and when applied to the bottom phases they allow improvement of backflashover rate. Adequate selection of the arrester configuration in the line can significantly improve lightning performance, and may reduce the financial burden. For the UK overhead lines, considering the low lightning strikes statistics (low value of GFD), no additional arrester protection is required for improving the lightning performance alone.

Energy stress analysis of ZnO surge arresters installed on the line was investigated. It was found that the energy requirements on the line arresters were moderate. The energy absorption studies were carried out for the line and stroke parameters which are essential in the selection process of line surge arresters. A negligible value of arrester failure rate for lightning strokes terminating on phase conductors (shielding failure) were found. This is seen as the main source of the risk of failure. In this case, arresters installed on other phases on the same tower and on the same phases in neighbouring towers did not help to share the total surge energy. No risk of arrester failure due to a stroke terminating on a shield wire or tower top (backflashover) were observed. Therefore, the possibility of arrester failure could be ignored while uprating the line.

Analysis of energy duty showed that the arrester type selected for the protection of the line considered in this study was adequate, thereby helping the reduction of the lightning impulse withstand level.

CHAPTER 7

ELECTRIC AND MAGNETIC FIELD PROFILES FOR UPRATED LINES

7.1 INTRODUCTION

Overhead transmission and distribution lines generate electric and magnetic fields in their vicinity. The source of the electric field is the potential on the conductors and the magnetic field is the current flowing through the line. Occupational or public exposure to these fields is of significant health concern [7.1, 7.2] and plays a role in defining "Width of Corridor (WoC)" of the line. According to National Grid [7.3], "*A corridor in UK parlance is a strip of land along a high-voltage power line where development is restricted*". Even though the UK current policy is not to have corridors, SAGE (Stakeholder Advisory Group on ELF EMF's (Extremely Low Frequency Electric and Magnetic Field)) says that the WoC on average should be set where the magnetic field falls to 0.4μT [7.3].

The electric field intensity is expected to increase in a voltage uprated line as the clearances are reduced together with an increased level of voltage. It is, therefore, necessary to calculate both electric and magnetic fields in the uprated line to ensure field limits are not exceeded.

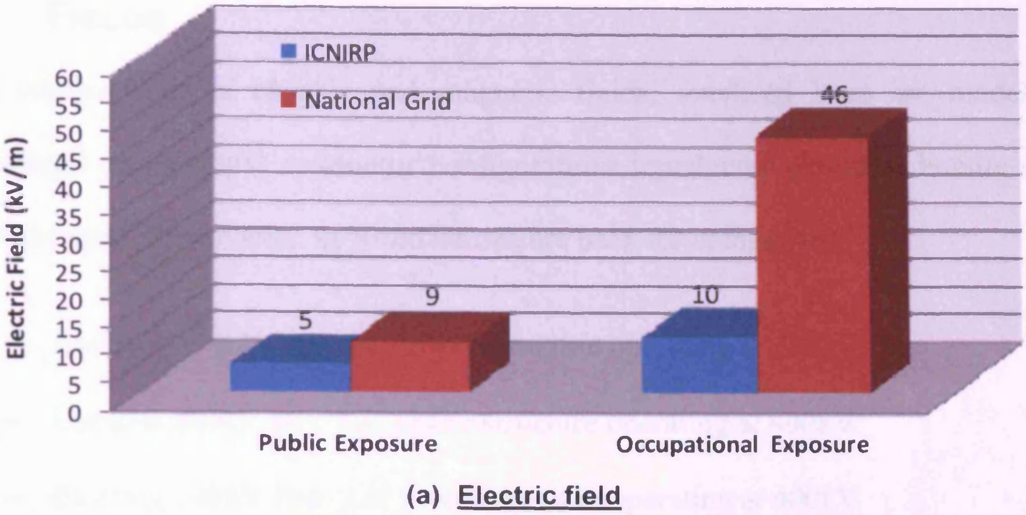
This chapter deals with the analysis of electric and magnetic fields in the uprated 400kV 'L3' line. The field profiles in different conditions are then compared with those of fields in existing 'L3' 275kV line and a standard 'L6' 400kV line which are common in the UK grid system. The field profiles for uprated lines are compared with the allowable limits of the EMF exposures. Horizontal and vertical contours are shown to observe whether the additional WoC is needed for uprated voltage level.

7.2 Limits on Exposure to Electric and Magnetic Fields

Different national and international guidelines are available, which advise on limiting exposure to electric and magnetic field. As indicated in Section 2.6 (Chapter 2), the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines [7.4] provides limits of exposure to electric and magnetic fields. These limits are set as per the IEEE standard procedure for measurement of electric and magnetic field from 50Hz AC power lines [7.5]. In the UK, the National Radiological Protection Board (NRPB) advises to follow ICNIRP guidelines [7.6]. National Grid (NG) which owns and operates the transmission lines in England and Wales; and other ENA member companies such as UK Power Networks, Scottish and Southern Energy, Scottish Power etc. follow recommendations made by SAGE [7.7] which is recognised by HM Government [7.8]. National Grid, therefore, publishes its own value as the limits to electric and magnetic fields [7.9]. Figure 7.1 compares National Grid specified limit of these fields for both public and occupational exposure with the values recommended by ICNIRP.

As can be seen in the figure, the NG limit for electric and magnetic field is 9kV/m and 360μT for public exposure and 46kV/m and 1800μT for occupational exposure. These values are greater than the ICNIRP specified limits of 5kV/m and 100μT for public exposure and 10kV/m and 500μT for occupational exposure. Therefore, the electric and the magnetic fields under any overhead line that fulfils the ICNIRP requirements will automatically fulfil the UK's utilities requirements.

Table 7.1 shows typical ground-level UK field levels for a 275kV and 400kV steel pylons used in the UK [7.9, 7.10].



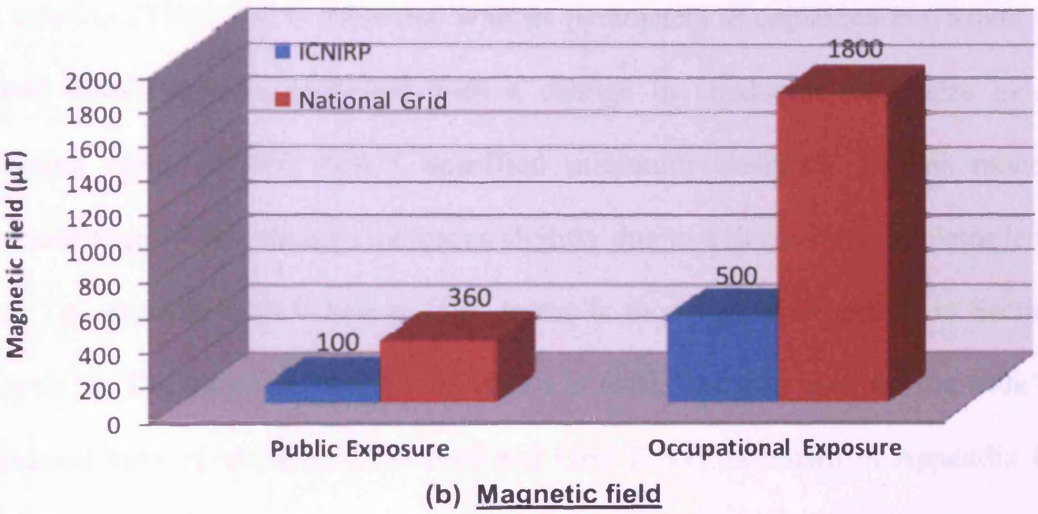


Figure 7.1: Comparison of National Grid specified electric and magnetic field limits with ICNIRP limits at power frequency (50Hz). Data source: [7.4, 7.9].

Table 7.1: Typical ground-level UK field levels from 275kV and 400kV overhead power lines [7.9, 7.10].

	Electric Field (kV/m)	Magnetic Field (μT)
Maximum Field (under line)	11	100
Typical Field (under line)	3 - 5	5 - 10
Typical Field (25m to side)	0.2 - 0.5	1 - 2

7.3 LINE MODEL FOR COMPUTATION OF ELECTRIC AND MAGNETIC FIELDS

For computation of electric and magnetic fields, overhead lines are modelled by horizontal and vertical conductor configurations, conductor diameter, bundle spacing and line span. Three lines, as listed below, are used for comparison:

- Existing 275kV line 'L3' tower structure operating at 275kV
- Uprated 400kV line 'L3' tower structure operating at 400kV
- Existing 400kV line 'L6' tower structure operating at 400kV

The existing 275kV line is modelled with its parameters as explained in Chapter 4. The uprated 400kV line is modelled with a change in conductor clearances to satisfy increasing value of IEC 60071 specified minimum clearance. In this model, the conductor vertical coordinates increases slightly due to a decrease in insulator length to 3.2m. The existing 400kV line in 'L6' tower is modelled as described in Section 5.5 (Chapter 5). The phase sequence ABC-CBA is used. The data used for the 400kV line, considered here, is obtained from National Grid [7.11] as shown in Appendix D. For this line, 400mm^2 ACSR Zebra conductor with diameter 28.62mm is used. Figure 7.2 shows conductor coordinates of the uprated and existing conventional lines used for the computation of electric and magnetic field. The physical width of the uprated 400kV line in L3 tower is 9.5m which is significantly less than the conventional 400kV line in L6 tower of which the width is more than 20.5m.

Two software are used to compute the fields along the line. SIGMA-Slp, which was used earlier for computation of overvoltages and surge arrester control, is also used here to compute electric and magnetic fields profiles at midspan of the line. Since, the SIGMA-Slp can only produce mid-span field profiles, the second software "Prgline-3D" has been extensively used [7.12]. The software is based on a three dimensional

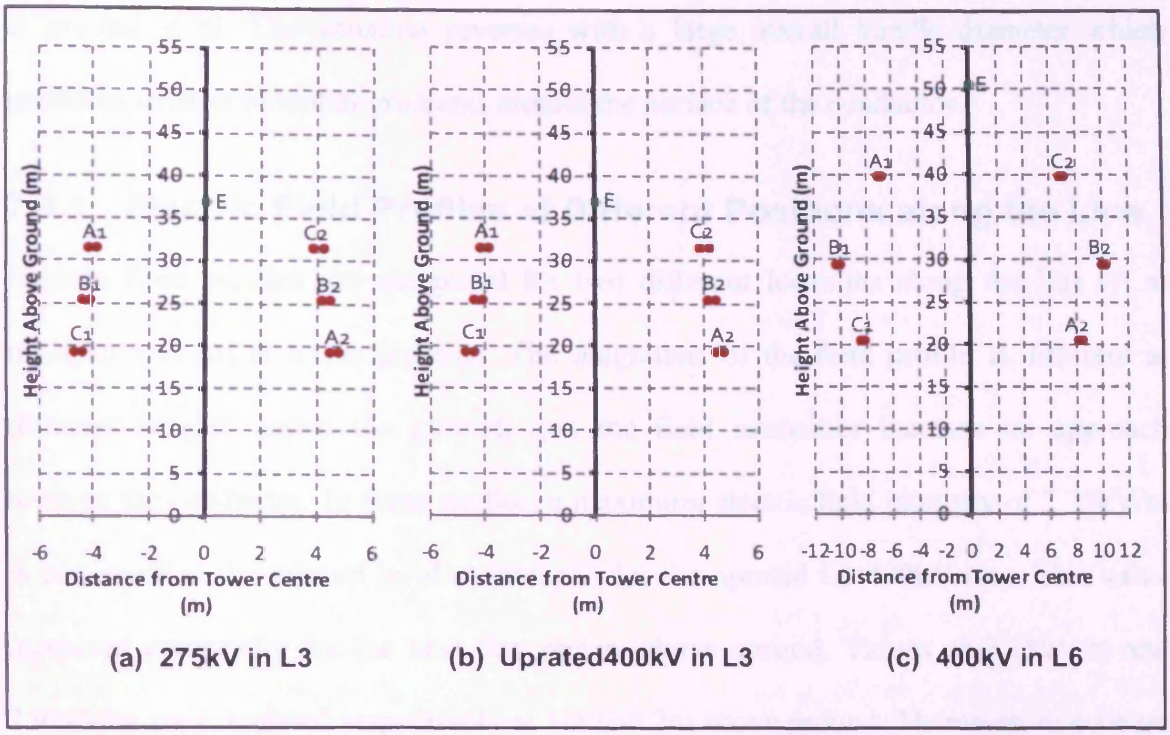


Figure 7.2: Conductor coordinates for computation of electric and magnetic fields used for uprated and conventional lines.

modelling of conductor geometry which allows the analysis of not only the aligned spans but also the complex geometry of line intersections [7.13]. For computation of electric field, a 2D model of the conductor using Maxwell's potential coefficient is used [7.12]. The magnetic field is computed by applying a discrete approximation of the Ampere-Laplace law in differential form [7.13]. Unless specified, results presented here are produced using Prgline3D software.

7.4 Computation of Electric Field

The magnitude of the electric field in an overhead line depends on several line parameters such as conductor-to-ground clearance, height of measurement above ground, conductor phase sequence and the bundle arrangement, its diameter and number of sub-conductors in a bundle. A conductor with a smaller diameter at the same voltage level produces higher electric field at the conductor surface resulting in higher potential gradients in the surrounding area. However, this produces low magnitude electric fields at ground level. The situation reverses with a large overall bundle diameter which produces smaller potential gradients around the surface of the conductor.

7.4.1 Electric Field Profiles at Different Positions along the Line

Electric filed profiles are computed for two different locations along the line (i) at midspan and (ii) at tower position. The magnitude of the field profile is different at different heights above the ground, and the field intensities increase on approach towards the conductor. In these studies, a maximum electric field intensity of 2.73kV/m is computed at the ground level at midspan for the uprated L3 400kV line. This value increased marginally for the next few meters above ground. Values of 2.75kV/m and 2.91kV/m are calculated respectively at 1m and 2m above ground. Therefore, to account for human exposure in the lower ground level, the electric fields are computed at a height of 1m above the ground as per the IEEE standard procedure for measurement of electric and magnetic fields [7.5].

Figure 7.3 shows the calculated electric field profiles at midspan under uprated and conventional lines. The results produced using both Prgline3D and SIGMA-Slp software showed exactly the same profiles. The calculated maximum electric field for

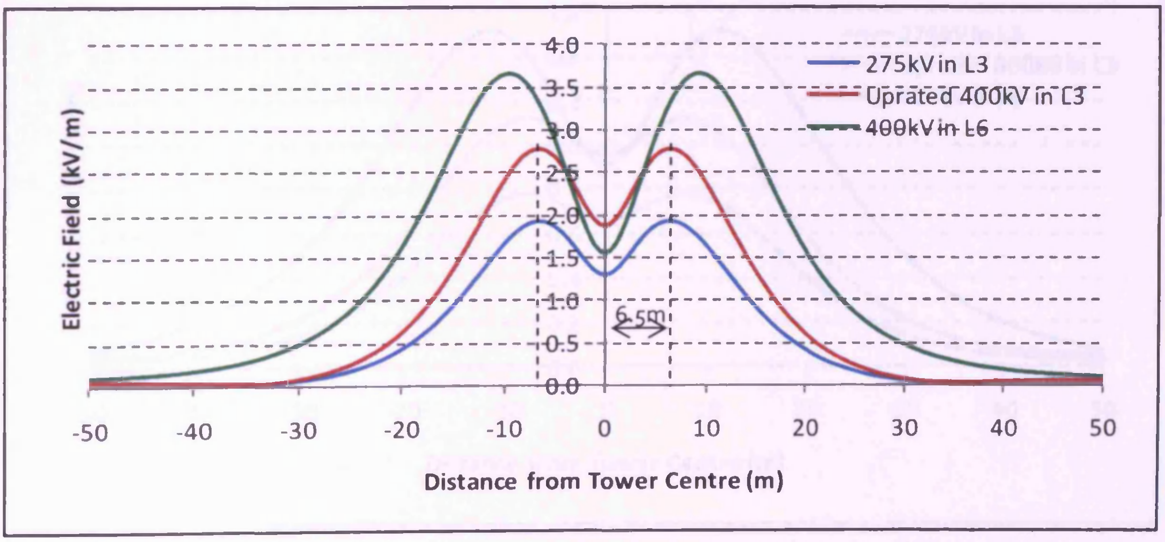


Figure 7.3: Electric field profiles at midspan under uprated and conventional line at 1m above the ground.

the existing L3 275kV line, the uprated L3 400kV line and the existing L6 400kV line are 1.92, 2.75 and 3.65kV/m respectively.

As expected, the electric field profiles in Figure 7.3 show that the uprated 400kV line has the same field corridor as the existing conventional 275kV line (before uprating) as both lines have the same maxima and minima positions. Both lines have maximum field intensity at 6.5m away from the centre of the tower. It is because the conductor separations remain the same while uprating the line. However, the electric field under the uprated line is greater than the existing 275kV line, which can be explained by the increase in voltage level in the system. The increase in voltage level results in an increase of the maximum electric field by 43%. The field produced by the uprated line (2.75kV/m) is, however, still lower than the ICNIRP specified maximum limit (5kV/m) for public exposure. Compared to the existing 400kV system with L6 tower structure, the uprated 400kV line using the L3 tower has a lower magnitude, and is confined within a narrower corridor.

Figure 7.4 shows the electric field profile at tower position. Here, the disturbance in electric field profile due to metal structure is ignored and only the effect of the height of

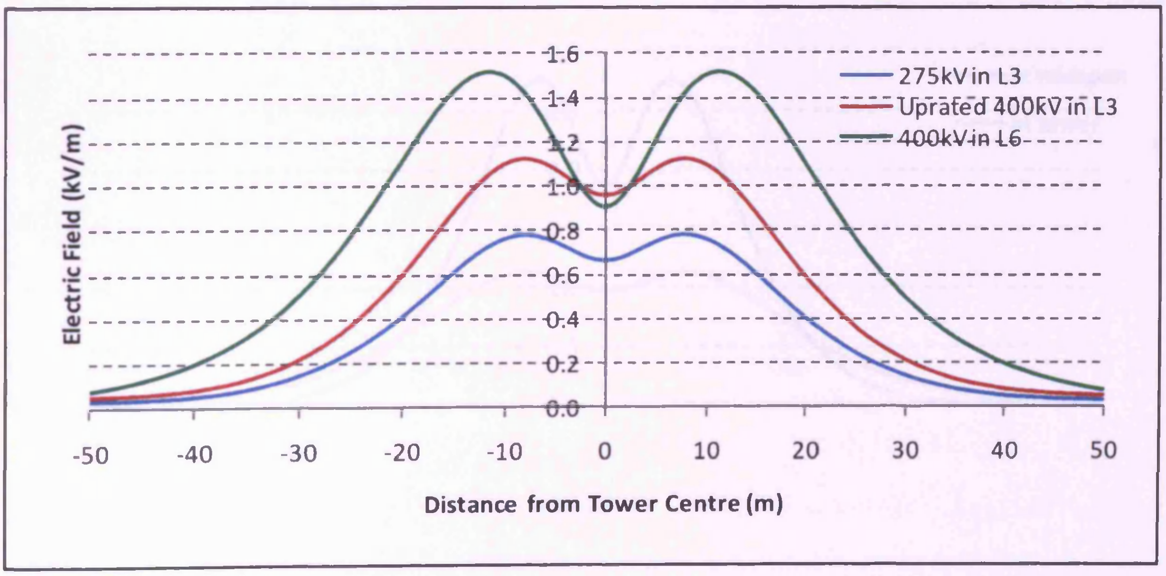


Figure 7.4: Electric field profiles at tower position under uprated and conventional lines at 1m above the ground.

the conductors at the tower attachment point is assessed. All other conditions remain the same as at midspan. At the tower position, the electric field profiles at 1m above ground level in all the lines considered follow the same pattern as at the midspan. Compared with the field intensity at midspan, the maximum electric field at the tower position is lower in magnitude (0.7, 1.1 and 1.5kV/m for L3 275kV line, uprated L3 400kV line and, L6 400kV line respectively). Figure 7.5 compares electric field profiles at 1m above ground level at midspan and at tower position for uprated L3 400kV line. The difference in electric field, in this case, is due to the difference in conductor height (because of sag) at two different positions. For the same line, the higher conductor produces lower electric field magnitudes at ground level near to line but shows higher magnitudes away from the line.

Figure 7.6 compares the field intensity 25m away from the centre of the line. Values computed are at 1m above ground at midspan and at a tower location. It can be seen that the field magnitudes of 0.25kV/m at midspan and 0.36kV/m at the tower position falls within the typical UK limit (0.2 – 0.5kV/m) as shown before in Table 7.1 and are much lower than the corresponding values of 0.86 and 0.76kV/m respectively for a

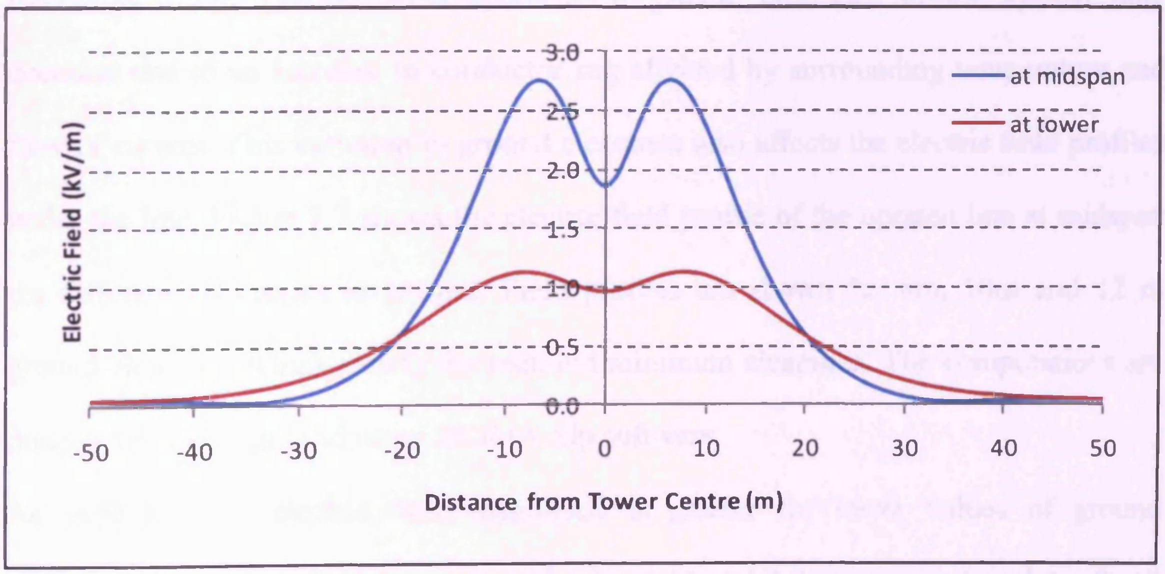


Figure 7.5: Comparison of electric field profiles at 1m above ground at midspan and at tower position for uprated L3 400kV line.

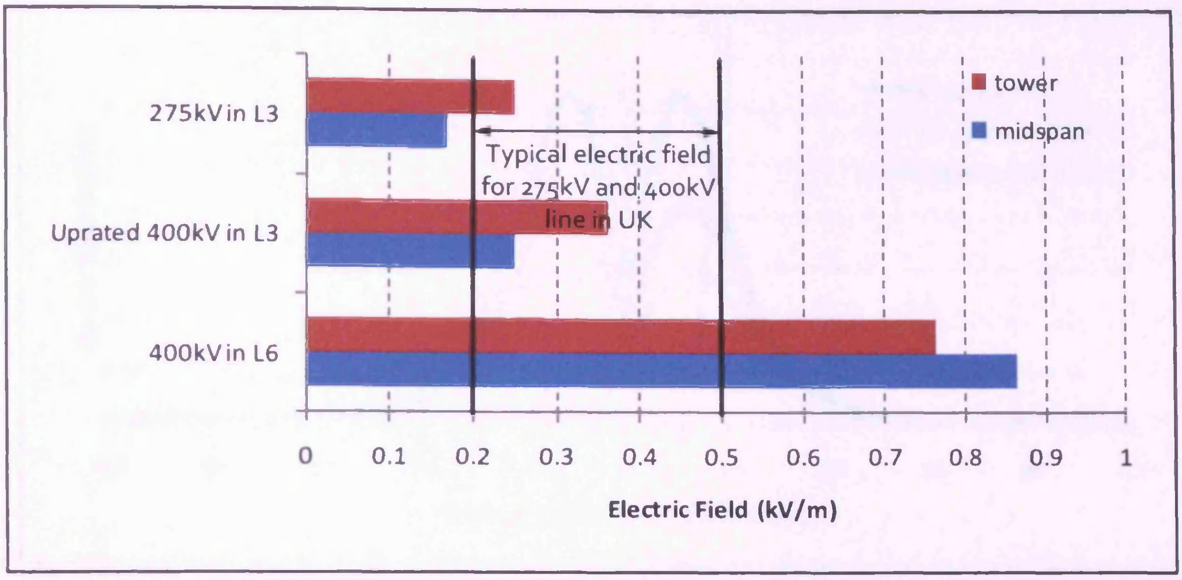


Figure 7.6: Electric field magnitude at 25m away from the centre of the line trail (1m above ground level) for L3 275kV, uprated L3 400kV and L6 400kV line.

conventional 400kV line. Therefore, the proposed uprated line produces significantly lower electric fields compared with a conventional L6 line at the same voltage.

7.4.2 Effect of Conductor-to-Ground Clearance

The uprated 400kV line with the proposed 3.2m insulator string will have a minimum phase-to-ground clearance of 12.3m. As shown earlier in Table 4.4 (Chapter 4), the minimum required ground clearance for a 400kV system in the UK and Northern Ireland is 7.3m. The available conductor-to-ground clearance in the system may decrease due to an increase in conductor sag affected by surrounding temperature and flow of current. This variation in ground clearance also affects the electric field profiles under the line. Figure 7.7 shows the electric field profile of the uprated line at midspan for different clearances to ground. Field profiles are shown for 8m, 10m and 12 m ground clearance which satisfy the required minimum clearance. The computations are done at 1m above ground using SIGMA-Slp software.

As expected, the electric field magnitude is greater for lower values of ground clearance. Maximum field intensities of 6.31, 4.16 and 2.91kV/m are found for 8, 10

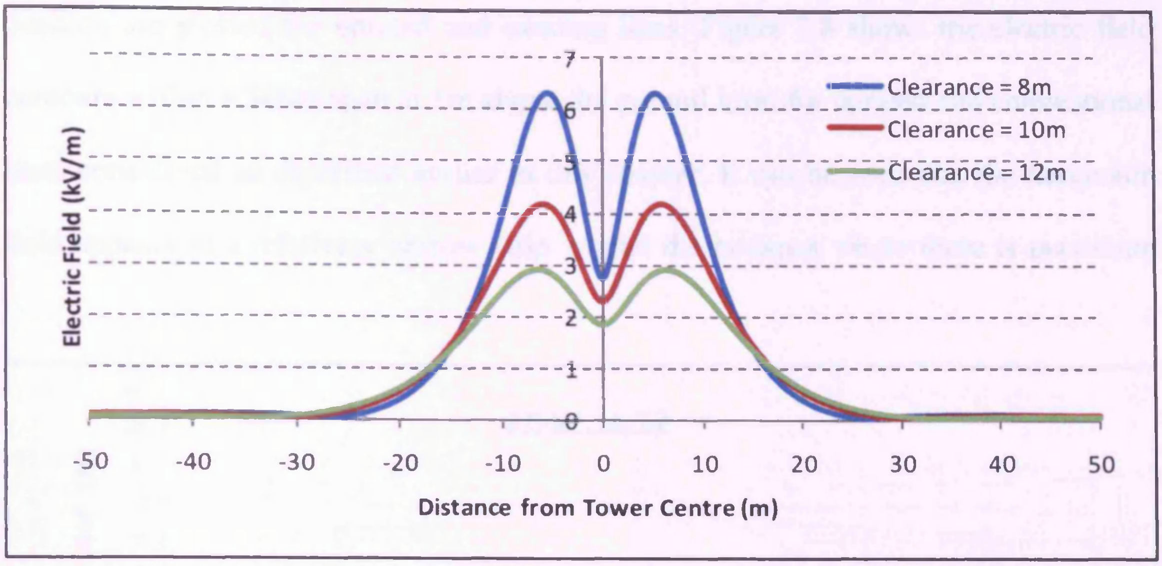


Figure 7.7: Electric field profile at midspan for different conductor-to-ground clearance. Values computed at 1m above ground (SIGMA-Slp Simulation).

and 12m ground clearance respectively. The electric field intensity of 6.31kV/m at minimum clearance level (8m) considered would breach the maximum permissible limit (5kV/m) of ICNIRP for public exposure. However, this value is within the limit of NG specification (9kV/m).

The field intensity can only be limited below ICNIRP limit for phase-to-ground clearance of 9.1m in which case the field intensity of 4.92kV/m is obtained. At this clearance level, the conductor will have 10.2m midspan sag. The line is modelled with midspan sag of 7.05m. Therefore, the conductors are only allowed for further sag up to approximately 3m to account for change in conductor temperature. However, the field intensities are within the NG specified limit and will not exceed 7kV/m for minimum required ground clearance (7.3m) for a 400kV system.

7.4.3 Electric Field Contours

It is also important to determine field levels along the transmission line corridor to help understand the WoC covered by the electric field. Horizontal contours of equi-level electric field lines within a span at 1m above ground and vertical contours at tower position are plotted for uprated and existing lines. Figure 7.8 shows the electric field contours within a 300m span at 1m above the ground level for uprated and conventional lines considered as described earlier in this chapter. It can be seen that the maximum field appears in a relatively narrow strip around the midspan where there is maximum

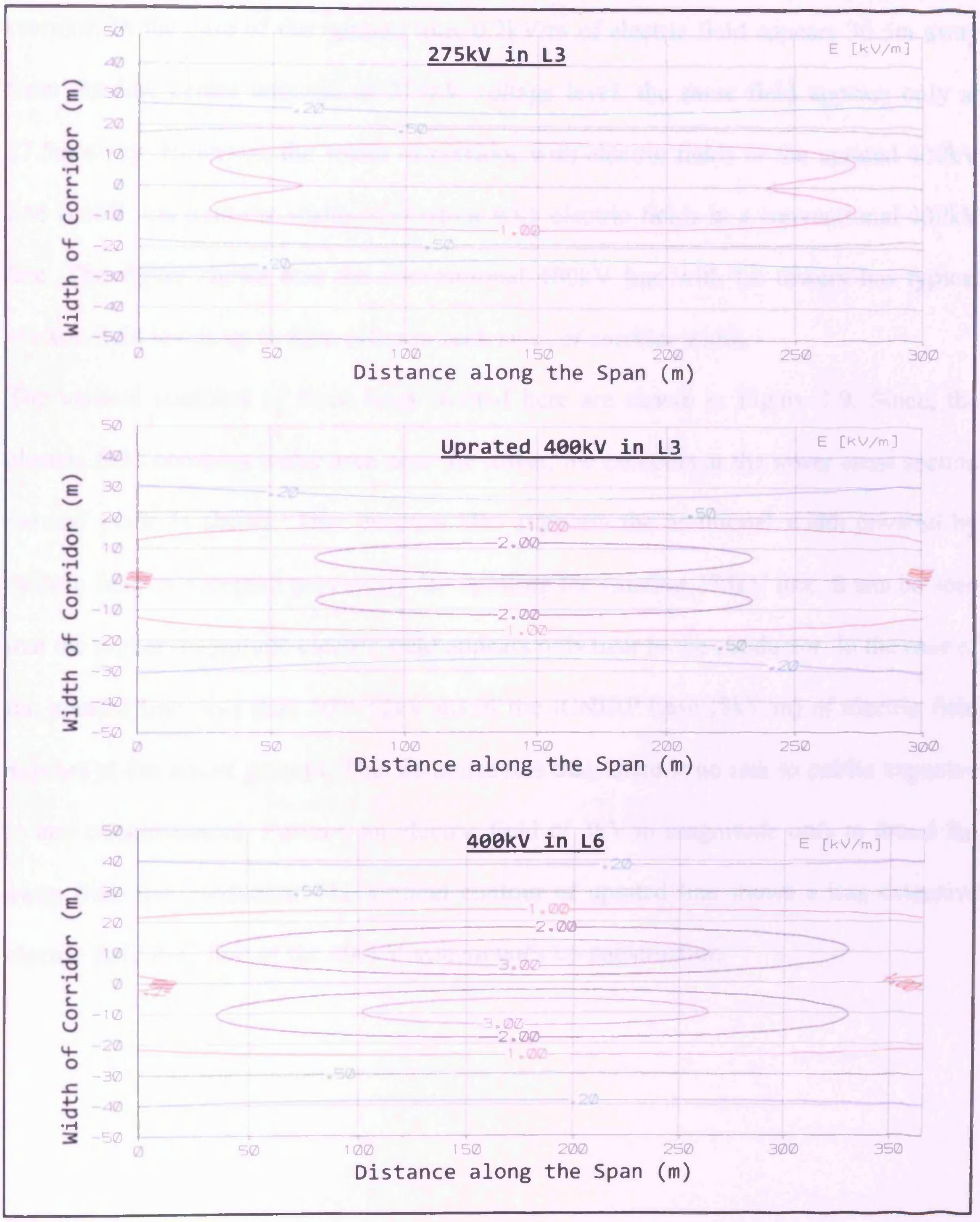


Figure 7.8: Electric field contour along a span for uprated and existing lines at 1m above ground.

sag. At the tower position, relatively low magnitude fields appear but spread over a wider area. While uprating the existing 275kV line, it is seen that the width of the line corridor affected by electric field intensities is slightly increased. Considering typical UK field levels (0.2kV/m - 0.5 kV/m) at 25m away from the line, the uprated line electric field covers approximately 6m (3m in each side of the line) additional width of corridor. In the case of the uprated line, 0.2kV/m of electric field appears 30.5m away from the line centre whereas at 275kV voltage level, the same field appears only at 27.5m away. However, the width of corridor with electric fields in the uprated 400kV line is still less than the width of corridor with electric fields in a conventional 400kV line. The figure shows that the conventional 400kV line with L6 towers has typical electric field levels up to 80m (40m in each side) of corridor width.

The vertical contours of three lines studied here are shown in Figure 7.9. Since, the electric field occupies wider area near the tower, the contours at the tower cross section vertical plane is shown. This diagram also supports the additional width covered by electric field as accepted previously for uprating the existing 275kV line. It can be seen that the higher magnitude electric field appears only near to the conductor. In the case of the uprated line, less than 50% (2kV/m) of the ICNIRP limit (5kV/m) of electric field appears at 8m above ground. This demonstrates that, there is no risk to public exposure in any circumstances. Further, an electric field of 3kV/m magnitude only is found 8m away from the conductor. The vertical contour of uprated line shows a less extensive electric field than that of the 400kV system with L6 construction.

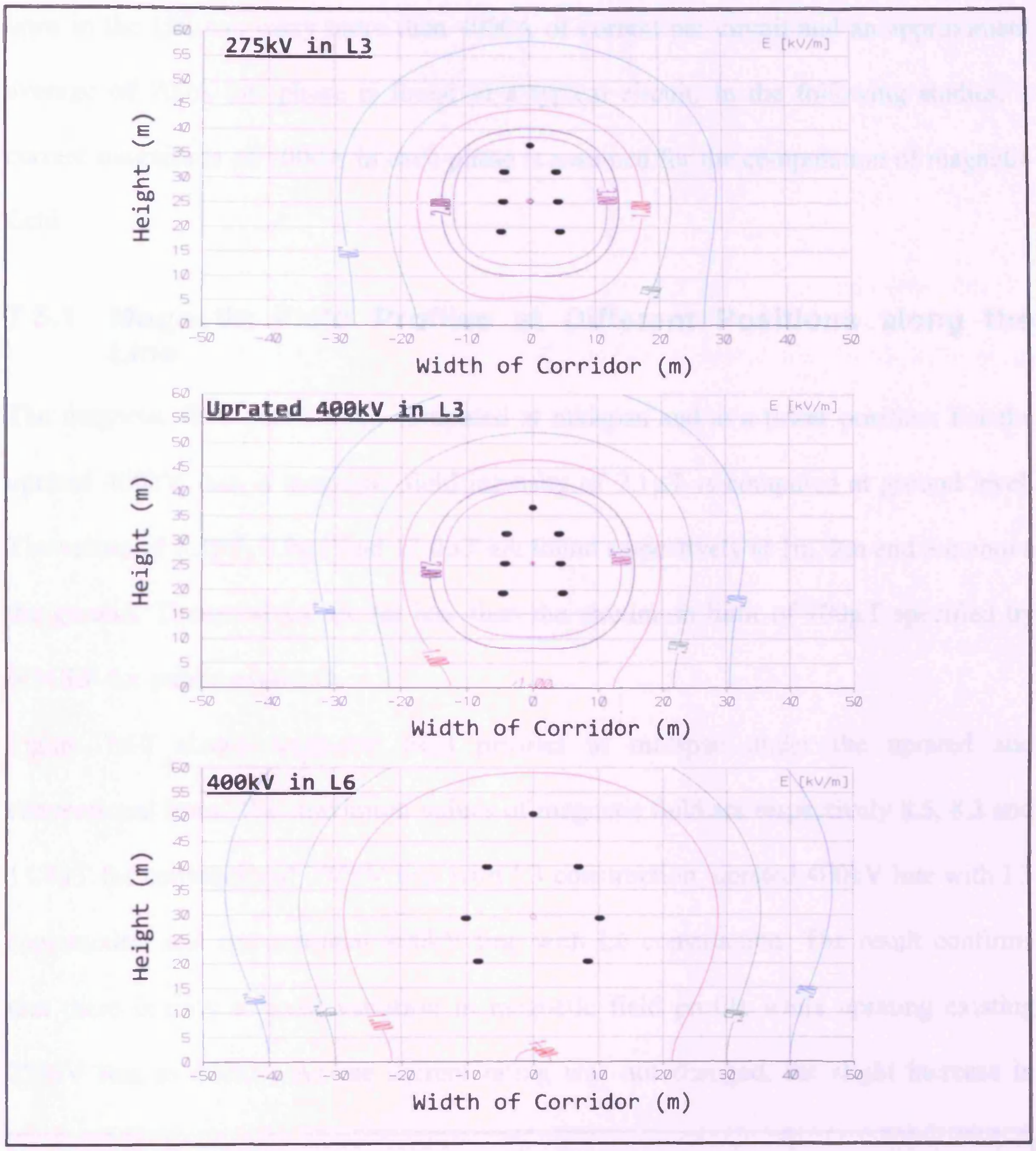


Figure 7.9: Electric field contour at tower cross section vertical plane.

7.5 COMPUTATION OF MAGNETIC FIELD

The magnetic field profiles and their contours for the uprated 400kV line are compared with that of the existing 275kV line with L3 construction and the 400kV line with L6 construction. In order to determine the requirement of additional WoC (determined by magnetic field), the magnetic field profiles at its horizontal contours are computed at 1m above ground level. According to National Grid [7.14], the highest rated transmission lines in the UK can carry more than 4000A of current per circuit and an approximate average of 700A per phase is found in a typical circuit. In the following studies, a current magnitude of 1000A in each phase is assumed for the computation of magnetic field.

7.5.1 Magnetic Field Profiles at Different Positions along the Line

The magnetic field profiles are computed at midspan and at a tower position. For the uprated 400kV line, a magnetic field intensity of 7.1μT is computed at ground level. The values of 8.3μT, 9.9μT and 12.0μT are found respectively at 1m, 2m and 3m above the ground. These values are far less than the maximum limit of 100μT specified by ICNIRP for public exposure.

Figure 7.10 shows magnetic field profiles at midspan under the uprated and conventional lines. The maximum values of magnetic field are respectively 8.5, 8.3 and 11.4μT for conventional 275kV line with L3 construction, uprated 400kV line with L3 construction and conventional 400kV line with L6 construction. The result confirms that there is only a small variation in magnetic field profile while uprating existing 275kV line to 400kV. As the current rating was not changed, the slight increase in

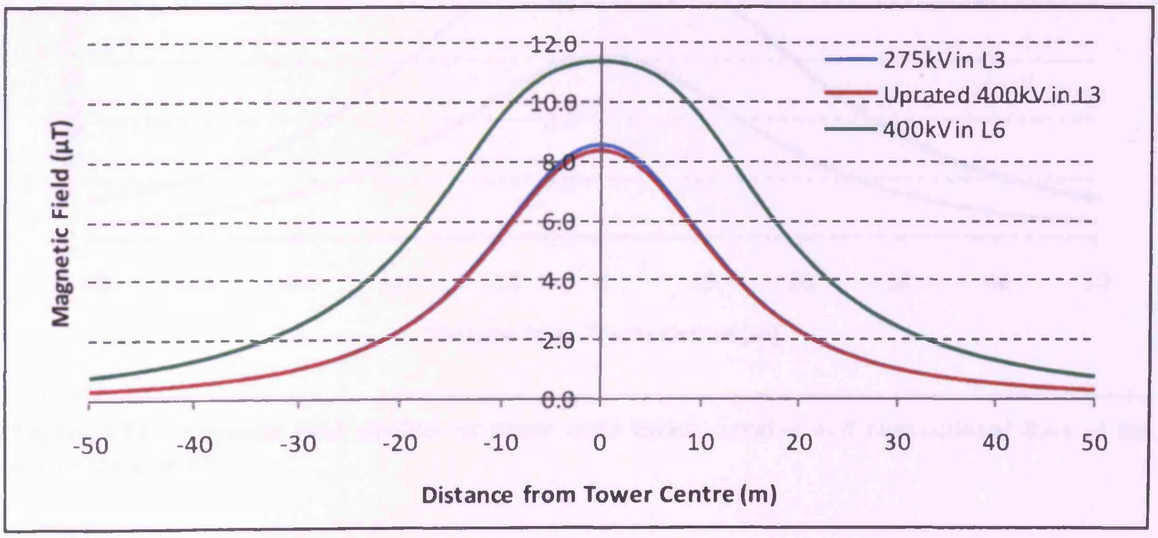


Figure 7.10: Magnetic field profiles at midspan under uprated and conventional lines at 1m above the ground.

conductor height for the uprated line results in a slightly lower magnetic field strength for a given height compared with the original 275kV line. The uprated line produced a lower magnetic field compared with the conventional L6, 400kV line assuming the same current loading.

Figure 7.11 shows the magnetic field profile at a tower position. Compared with the field at midspan, the magnetic field at tower position is lower due to the increase in conductor height. Values of 3.1μT, 3.0μT and 5.0μT are computed for conventional 275kV, uprated 400kV and conventional 400kV lines respectively.

Figure 7.12 compares the field intensity at 25m away from the tower in horizontal direction. Values are computed at 1m above ground at midspan and at tower position. In this case, the magnetic field of the uprated line is within the typical UK field limits (1 – 2 μT). The field magnitude of 1.49μT at midspan and 1.02μT at tower node is obtained which again is lower than the corresponding of 3.5μT and 2.25 μT for a conventional L6 400kV line.

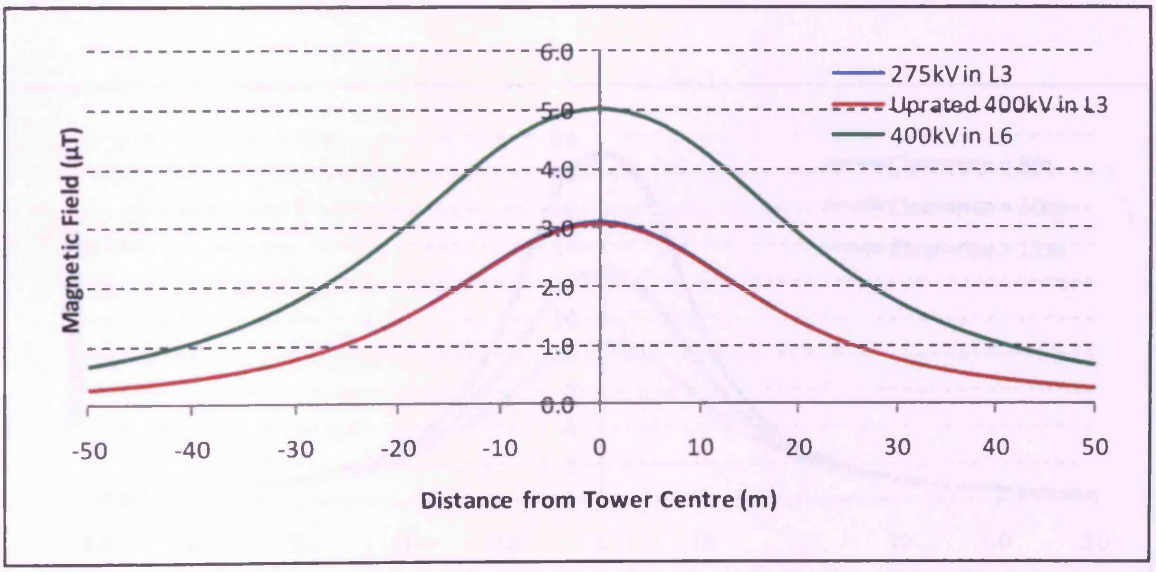


Figure 7.11: Magnetic field profiles at tower node under uprated and conventional lines at 1m above the ground.

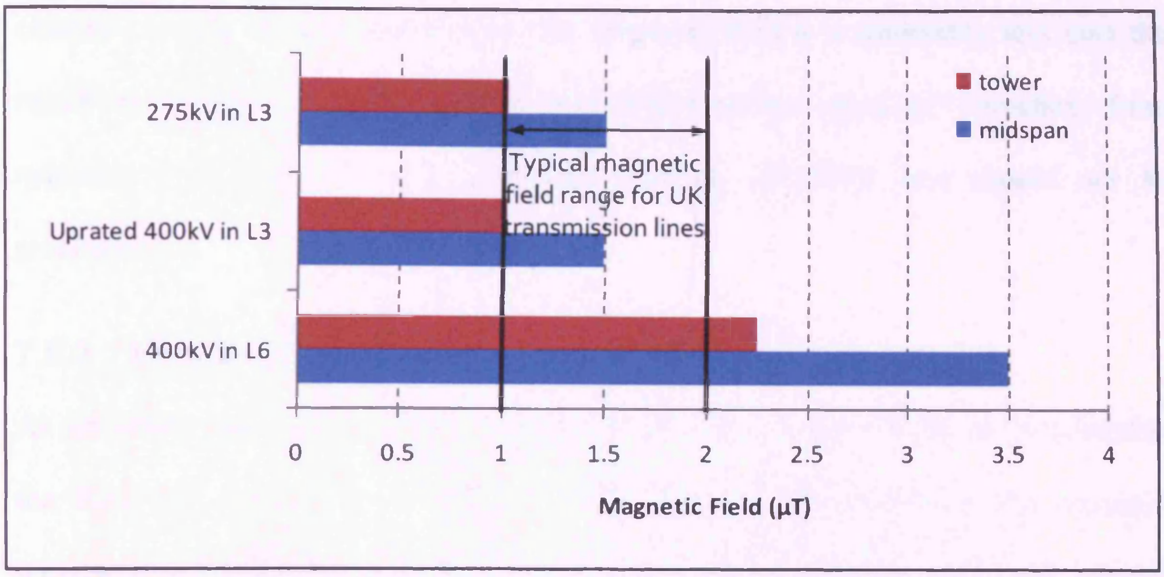


Figure 7.12: Magnetic field at 25m away from the centre of the line trail.

7.5.2 Effect of Conductor-to-Ground Clearance

The effect of variation in conductor-to-ground clearance for magnetic field under the uprated 400kV line at midspan is shown in Figure 7.13. Magnetic field magnitudes are shown for 8m, 10 and 12m ground clearances. As expected, the magnetic field magnitude is higher for lower ground clearance. Maximum fields of 19.0, 12.5 and 8.6μT are found for 8, 10 and 12m ground clearances respectively. Even for the lowest

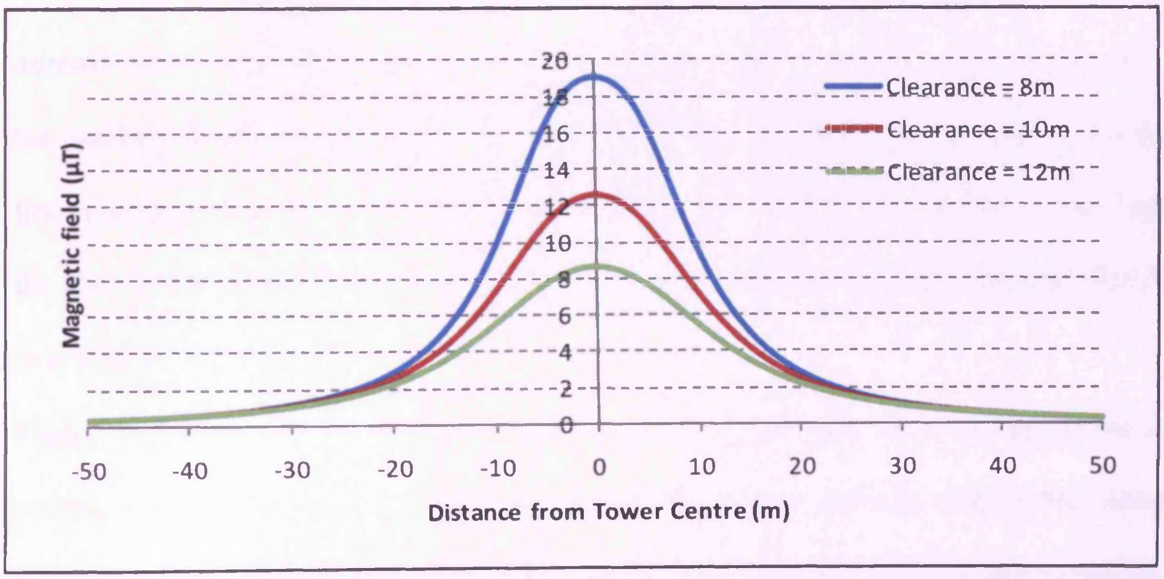


Figure 7.13: Magnetic field profile at midspan for different conductor-to-ground clearance. Values computed at 1m above ground (SIGMA-Slp Simulation).

clearance level (8m) considered here, the magnetic field is considerably less than the maximum permissible limit (100μT) of ICNIRP public exposure. Therefore, from magnetic field point of view, proposed uprating of 275kV line should not be problematic.

7.5.3 Magnetic Field Contours

As described earlier, the magnetic field magnitude is an important factor to determine the WoC. In order to find magnetic field levels on a transmission line corridor, horizontal contours of equi-level magnetic field lines within a span and vertical contours at midspan are plotted for uprated and conventional lines. Figure 7.14 shows the magnetic filed contours within a span at 1m above the ground for uprated and conventional lines considered in this study. Unlike electric field contours, the maximum magnetic field magnitude appears over a relatively wider strip around the midspan where there is maximum sag and these field regions at tower position occupy narrow corridor. The magnetic field region shrinks when the conductor height is increased. It is to be noted that the magnetic field in the uprated line does not require any additional WoC. As can be seen in the figure, the WoC occupied by magnetic field along a span in uprated 400kV line is the same as that of 275kV line before uprating. In both the cases, the magnetic field of 1μT appears to be approximately at a distance 30m away from the line centre and does not exceed the typical UK field level of 1 – 2 μT at 25m away from the line. Further, WoC of the uprated line is lower than that of a conventional 400kV line with L6 construction.

Figure 7.15 shows the contours of magnetic field magnitudes in a vertical plane at midspan. It is clear that only the low magnitude magnetic fields are seen by the public which itself is within the safe limit. A value of 100μT appears to be at approximately 2.5m away from conductors. However, these fields can only be exposed to skilled person (occupational exposure) for which the safety limit is 500μT as per ICNIRP. Therefore, from the magnetic field point of view, there is no risk of public and occupational exposure from the line.

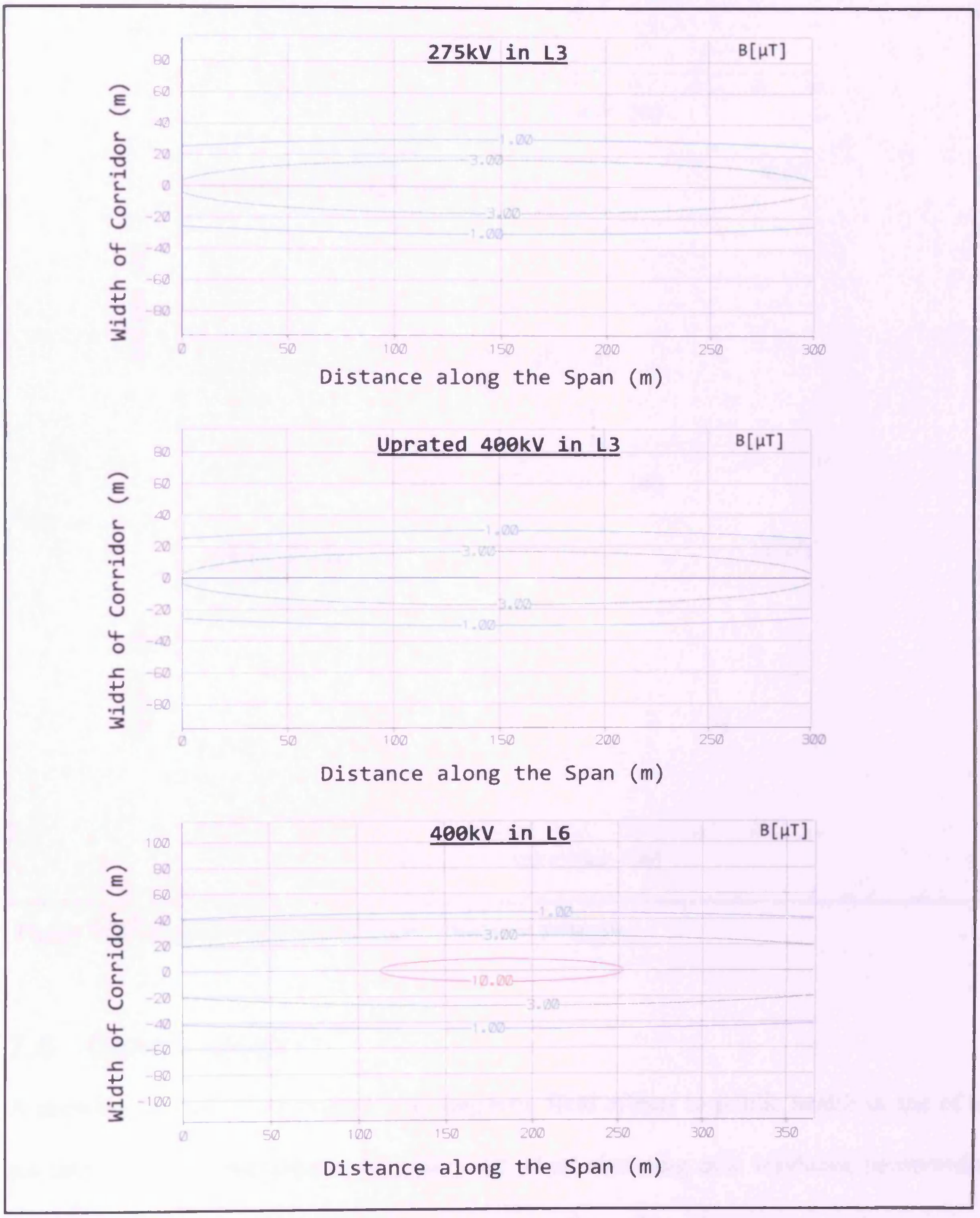


Figure 7.14: Magnetic field contour along a span for uprated and conventional lines.

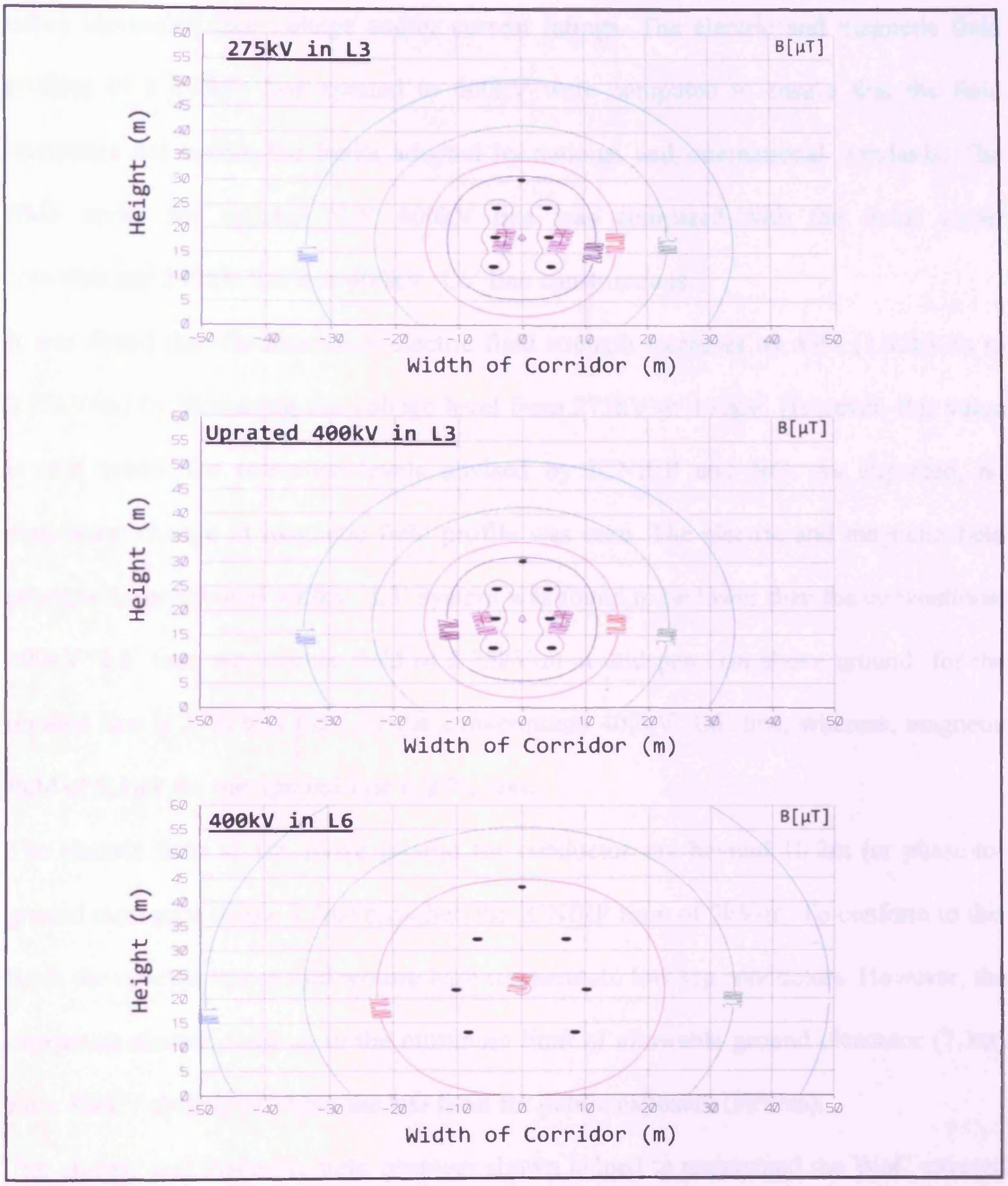


Figure 7.15: Magnetic field vertical plane contour at midspan.

7.6 CONCLUSIONS

A growing concern over electric and magnetic field effects to public health is one of a number of issues that need to be addressed when obtaining new wayleave permission for the construction or modification of overhead lines. Therefore, uprating the existing lines should also be examined for the risk of increasing the intensity of such fields when either increasing line voltage and/or current ratings. The electric and magnetic field profiles of a 275kV line uprated to 400kV were computed to ensure that the field intensities are within the limits adopted by national and international standards. The EMF under the uprated 'L3' 400kV line was compared with the fields under conventional 275kV 'L3'and 400kV 'L6' line constructions.

It was found that the maximum electric field strength increases by 43% (1.92kV/m to 2.75kV/m) by increasing the voltage level from 275kV to 400kV. However, this value is still below the reference levels advised by ICNIRP and NG. As expected, no significant change in magnetic field profile was seen. The electric and magnetic field strength in the uprated 400kV 'L3' system was found to be lower than the conventional 400kV 'L6' line. An electric field of 2.75kV/m at midspan (1m above ground) for the uprated line is 25% less than for the conventional 400kV 'L6' line, whereas, magnetic field of 8.3μT for the uprated line is 27% less.

The electric field at 1m above ground for conductor sag beyond 10.2m (or phase-to-ground clearance below 9.1m) breached the ICNIRP limit of 5kV/m. To conform to this limit, the uprated line would require high temperature low sag conductors. However, the maximum electric field up to the minimum limit of allowable ground clearance (7.3m) for a 400kV system is within the NG limit for public exposure (9kV/m).

The electric and magnetic field contours shown helped to understand the WoC covered by these fields. The magnetic field contours showed no requirement of additional WoC when uprating the 275kV line to the 400kV.

CHAPTER 8

GENERAL DISCUSSIONS, CONCLUSIONS AND, FUTURE WORK

In this research work, technical issues for voltage uprating of overhead transmission lines are methodically investigated. A common L3, 275kV line in the existing UK transmission system is considered as a case study for uprating to the next voltage level of 400kV system. The research investigation concentrated on identifying the factors that govern an overhead line design for voltage uprating purposes. These include the physical location and spacings of conductors, the type and the length of insulators, and overvoltage protection measures. More importantly, the recommendations and specifications of current national and international standards were carefully considered. Where applicable, constraints due to practical limitations were considered.

Considering a case of a 275kV line, several options for uprating overhead transmission lines were investigated. These includes the substitution of existing insulator strings with a composite polymeric insulator to provide high creepage and the use of modern protective device to control overvoltages in the system such that the minimum required clearances as per the IEC 60071 for 400kV system are satisfied. A reverse concept of reducing the minimum required clearances by controlling switching and lightning overvoltage levels in the system was proposed. It was shown that the application of ZnO surge arresters on the line can effectively reduce the overvoltage level in the system which allows the implementation of the lower values of IEC standard switching and lightning impulse withstand levels. As a result, it is possible to use compact conductor configurations by reducing air clearances for the uprated voltage level. It was also shown that the use of appropriate configuration of line surge arresters can optimise the number of surge arresters along the line without compromising the system's targeted performance and thereby reducing the financial burden. Satisfactory lightning and switching performance of the line in uprated voltage level was obtained. The electric and magnetic field magnitudes were shown to be comparable to those of the line before uprating.

The extensive literature review carried out primarily in this research highlighted different techniques used worldwide for overhead transmission and distribution line uprating. It was found that the need for uprating overhead lines was first encountered in the mid fifties, followed by several cases of line uprating to increase power transfer capability. The extensive review of individual line uprating cases from various parts of the world revealed that, in the majority of the cases, the line power transfer capability was increased by increasing its current rating. Very few projects of voltage uprating of lines were realised as this is understood to be expensive due to the need for increasing the capacity of terminal substations.

There are two major technical issues identified which need to be addressed while considering voltage uprating of overhead lines: One is the larger conductor air clearance requirements to be satisfied at the higher voltage level compared with the existing line structure, and the other one is to assess the insulation level required to withstand the overvoltages due to power frequency and transient surges. The recommendations made by different national and international standards such as IEC, IEEE, BSEN, ENATS etc. were extensively considered to identify key actions for uprating an existing 275kV line with L3 towers to a 400kV system. Recommendations made by EPRI and CIGRE guidelines were also taken into account to build a strong technical foundation for the proposed technique for voltage uprating.

Current practice for air clearances in high voltage transmission networks adopts the highest recommendations of IEC 60071, and in some cases, with an extra margin for security of supply. These clearances are usually more than sufficient for a 1050kV switching impulse withstand level and a 1425kV lightning impulse withstand level. In the process of uprating an overhead line, there is flexibility from IEC 507 to reduce the switching impulse withstand level to 850kV and the lightning impulse withstand level to 1050kV. Such reductions have the potential to develop compact overhead line configurations or offer significant flexibility when voltage-uprating line. The solutions sought in this research investigation aim to keep existing tower structures and uprate the operating voltage to higher levels through the replacement of insulator strings and control of switching and lightning overvoltages introducing extensive use of Zinc-Oxide surge arresters.

Even though it was found that the conductor phase-to-phase clearances at transmission level are dominated solely by the switching overvoltage level, the phase-to-earth clearance requirement of the withstand voltage combinations for 400kV system considered here were found dictated either by lightning overvoltages or have equal influence of both switching and lightning overvoltages. The influence of each overvoltage in a line was found dependent on the set of lightning and switching overvoltage levels to be considered for the line design process. In order to meet the required insulation level for higher voltages, additional creepage requirements depending upon the site pollution level up to 3720mm was calculated for the L3 line case study.

For the L3 line considered here, it was found that the phase-to-earth clearance under still air condition only is insufficient. However, all other clearances such as phase-to-ground and phase-to-phase are sufficient enough for 400kV system operation. Under wind load, the reduced clearances due to insulator swing up to 35^0 was also found within the acceptable limits for all types of overvoltages considering that the clearance requirements under wind load reduces by a factor of 0.7 compared with the clearance in still air condition. In order to satisfy the additional phase-to-earth clearance requirement for 400kV system, a 3.2m insulator with minimum creepage of 12096mm was found appropriate. The use of composite polymeric insulators was proposed as one of the options for uprating the case study line. The characteristics such as high mechanical strength, light weight, hydrophobicity, low cost and their excellent performance under polluted environment can meet the requirement of additional creepage for voltage uprating. This technique can satisfy the requirement of IEC specified phase-to-earth clearance for 400kV system.

However, such a short polymeric insulator with the required creepage length is not readily available as a standard product from manufacturer. An alternative solution to satisfy the constraints problem is through the control of the stresses to which the line is subjected to. Therefore, instead of developing techniques to satisfy the required minimum clearance, it is proposed to use the lower combination of lightning and switching overvoltage withstand levels so that the minimum required clearances for 400kV system could be reduced. In the UK, 400kV system is designed for lightning and switching withstand level of 1425kV and 1050kV respectively, and these voltage level require air clearances of at 2.6m. From the analysis carried out in this work, it was demonstrated that a system with a lightning impulse withstand level of 1300kV and switching impulse withstand level of 950kV can be adequately protected with 2.4m air clearances, and in accordance with IEC 60071 recommendations. Adopting such approach for the uprating of the L3 line would not require any structural modification of the towers. For further security, the use of line surge arresters would ensure adequate and efficient control of both switching and lightning overvoltages.

The application of different line surge arrester configurations for switching overvoltage control showed that the arresters only at the line ends can reduce the overvoltage level below the targeted withstand level of 950kV. However, the control of lightning overvoltages needs in-depth study of the arrester location. In the case of shielding failure, arresters at the top two phases only of the line are sufficient to control the overvoltages to within the targeted value of 1300kV. On the other hand, overvoltages due to backflashover are influenced by the tower footing resistance value, and the arresters alone could not control the overvoltages to within the limits for high tower footing resistance values. Hence, it is necessary to identify the possibility of reducing the footing resistance value before undertaking voltage uprating of the line. This investigation has shown that up to a 40Ω footing resistance, deploying surge arresters at the bottom phase conductors only was sufficient to control the lightning overvoltage within the targeted limit.

The line arrester application analysis has revealed that the top conductors are prone to shielding failure strikes whilst the bottom conductors are more likely to be subjected to backflashover lightning surges. Although the arresters at the top two phases only are sufficient to protect the line against lightning having low footing resistance values, this configuration alone was not effective for high footing resistance values, as it cannot protect the line from backflashover occurring at the bottom phase conductors. In this case, arresters at top two and bottom two conductors were required.

Distribution of energy stress in surge arresters along the line showed that the class-3 arrester chosen in this study was not highly stressed. Only 1% of the overvoltage scenarios is likely to exceed 10% of the arrester energy capability and, therefore, negligible risk of arrester failure was observed due to the shielding failure.

The intensity of electric and magnetic fields around the lines were considered as the primary environmental concern. The effect of increasing the voltage rating of the line and possible change of conductor heights on electric and magnetic field profiles were observed. It was demonstrated that the magnetic field profiles for the uprated line did not have any significant change compared to the original 275kV operation, and was found to be better than the conventional 400kV line with L6 tower structure. Even though the electric field intensity was found to be higher than that of the line before uprating, the values are within the ICNIRP specified limits and are lower than the conventional 400kV system. It was found that the uprated 400kV line required no additional wayleave.

8.1 Future Work

In this thesis, important technical issues for voltage uprating were addressed. However, the financial issue is another important parameter that plays a key role in the decision making process. Further to this investigation, the study could be extended to address such issues. Two important points could be considered. First, the uprating is associated with the performance analysis of the line to be uprated which is directly associated with the cost. Therefore, the cost of uprating an existing line could be compared with the cost of building a new line. Second, the comparison of cost versus benefits of uprating is essential.

Together with the study of overhead transmission line uprating, it would be beneficial to study the voltage uprating for low voltage distribution systems. Different approaches for uprating low voltage lines are required, especially for a line with wood poles where pin insulators are generally used. The author has done some of the basic analysis in this part of the work the results of which were published in a conference paper, as shown in Appendix E. However, in depth analysis of this part of voltage uprating could be subject to future work.

REFERENCES

CHAPTER 1

1.1 EIA, "International Energy Outlook 2009", Energy Inform. Admin., U.S. Dept. of Energy, Washington DC, USA, Rep. DOE/EIA-0484(2009), May 2009.

1.2 IEA, "Key World Energy Statistics 2009", International Energy Agency, Paris, France, 2009.

1.3 *Guidelines for Increased Utilization of Existing Overhead Transmission Lines*, CIGRE WG B2.13, Brochure 353, Aug. 2008.

1.4 H. Griffiths and N. Pilling, "Earthing," in *Advances in High Voltage Engineering*, A. Haddad and D. Warne, Eds. Stevenage, UK : IET, 2004, ch. 8, pp. 349-413.

1.5 NG, "2007 Great Britain Seven Year Statement," National Grid, Warwick, UK, May 2007.

1.6 J. M. Ferguson and R. R. Gibbon, "Overhead Transmission Lines – Refurbishment and Developments," *IEE Power Eng. Journal*, vol. 8, no. 3, pp. 109-118, Jun. 1994.

1.7 S. Butler, "UK Electricity Networks: The Nature of UK Electricity Transmission and Distribution Networks in an Intermittent Renewable and Embedded Electricity Generation Future," MSc and/or DIC thesis, Imperial College of Science, Technology and Medicine, Univ. London, UK, Sep. 2001.

1.8 NG, "National Electricity Transmission System Seven Year Statement," National Grid, Warwick, UK, May 2010.

1.9 ENSG, "Our Electricity Transmission Network: A Vision for 2020," Electricity Network Strategy Group, UK, Rep. ENSRG 2009-026, Jul. 2009.

1.10 NG, "Bramford to Twinstead 400kV Overhead Line Project – Strategic Optioneering Report", National Grid, Warwick, UK, Oct. 2009.

1.11 NG, "Proposed Spennymoor to Norton 400kV Overhead Line – Environmental Statement," National Grid, Warwick, UK, Jul. 2009, vol. I.

1.12 J. R. Daconti and D. C. Lawry, "Increasing Power Transfer Capability of Existing Transmission Lines," *proc. IEEE/PES T&D Conf. and Expo.*, Dallas, USA, Sep. 2003, pp. 1004-1009.

1.13 S. J. Piernot and J. Leahy, "Maximize the Capacity of Your Transmission Lines," *porc. IEEE/PES T&D Conf. and Expo.*, Atlanta, GA, USA, Oct.-Nov. 2001, pp. 391-396.

1.14 *Transmission Line Uprating Guide,* Document no. 1000717, EPRI, Palo Alto, CA, USA, Nov. 2000.

1.15 T. M. Sekili and G. U. Martinez "Uprating Double-Circuit Transmission Lines 115kV to 230kV," in *Sargent & Lundy Transmission & Substation Conf.*, Chicago, IL, USA, Nov. 1982.

1.16 F. Soto, D. Alvira, L. Martin, J. Latorre, J. Lumbreras, and M. Wagensberg, "Increasing the Capacity of Overhead Lines in the 400kV Spanish Transmission Network: Real Time Thermal Ratings," *CIGRE Session*, Paper 22-211, Paris, 1998.

1.17 A. L. Tukachinsky, "Uprating of Power Transmission Lines in Israel Electric Corp.," *proc. The 21st IEEE Conv. of the Elec. and Electron. Engineers in Israel*, Tel-Aviv, Israel, Apr. 2000, pp. 314-317.

1.18 R. Stephen and D. Muftic, "Determination of the Thermal Rating and Uprating Methods for Existing Lines," *CIGRE Session*, Paper 22-305, Paris, 2000.

1.19 M. L. Lu, G. Pfrimmer, and Z. Kieloch, "Upgrading an Existing 138kV Transmission Line in Manitoba," in *IEEE Power Engineering Society General Meeting*, Montreal, Canada, Jun. 2006.

1.20 I. Zamora, A. J. Mazon, R. Criado, C. Alonso, and J. R. Saenz, "Uprating using High-temperature Electrical Conductors," in *16th Int. Conf. and Exhibition on Electricity Distribution*, Amsterdam, Netherlands, Jun. 2001.

1.21 M. J. Tunstall, S. P. Hoffmann, N. S. Derbyshire, and M. J. Pyke, "Maximising the Ratings of National Grid's Existing Transmission Lines using High Temperature, Low Sag Conductor," *CIGRE Session*, Paper 22-202, Paris, 2000.

1.22 *Conductors for the Uprating of Overhead Lines*, CIGRE WG B2.12, Brochure 244, Apr. 2004.

1.23 D. M. Larruskain *et al.*, "Power Transmission Capacity Upgrade of Overhead Lines," in *Int. Conf. on Renewable Energy and Power Quality*, Palma de Mallorca, Spain, Apr. 2006.

1.24 S. C. Nogales *et al.*, "HTLS and HVDC Solutions for Overhead Lines Uprating," in *11th Spanish-Portuguese Conf. on Elect. Eng.*, Zaragoza, Spain, Jul. 2009.

CHAPTER 2

2.1 *Oxford Paperback Dictionary, Thesaurus, and Wordpower Guide*, C. Soanes *et al.*, Ed. Oxford, UK: Oxford University Press, 2001.

2.2 S. R. Roget, *A Dictionary of Electrical Terms*, 4th ed. London: Sir Isaac Pitman & Sons, Ltd., 1944.

2.3 *Guidelines for Increased Utilization of Existing Overhead Transmission Lines*, CIGRE WG B2.13, Brochure 353, Aug. 2008.

2.4 I. Albizu, A. J. Mazon, and I. Zamora, "Methods for Increasing the Rating of Overhead Lines," *proc. IEEE Russia PowerTech Conf.*, St. Petersburg, Russia, Jun. 2005.

2.5 S. Narain, D. Muftic, B. Jacobs, and P. Naidoo, "Uprating of 275kV Lines to 400kV as Part of a Contingency Plan for Generation Integration," in *IEEE/PES T&D Conf. and Expo. : Latin America*, Caracas, Venezuela, Aug. 2006.

2.6 J. G. Hanson, "Upgrading Transmission Lines," *proc. IEEE/PES T&D Conf.*, Dallas, USA, Sep. 1991, pp. 824-827.

2.7 E. L. C. Larson, M. Broschat, and R. L. Thompson, "Transmission Line Uprating 115-kV to 230-kV Electrical and Structural Design," *IEEE Trans. Power App. Syst.*, vol. PAS-86, no. 5, pp. 539-546, May 1967.

2.8 *Transmission Line Uprating Guide,* Document no. 1000717, EPRI, Palo Alto, CA, USA, Nov. 2000.

2.9 *Management of Existing Transmission Overhead Lines*, CIGRE WG B22.13, Brochure 175, 2000.

2.10 *How OH Lines are Re-designed for Uprating / Upgrading – Analysis of the Answers to the Questionnaire*, CIGRE WG B2.06, Brochure 294, Jun. 2006.

2.11 A. Meier, "Transmission and Distribution," in *Electric Power Systems: A Conceptual Introduction*. New Jersey, USA: Wiley-Interscience, 2006, ch. 6, pp. 144-194.

2.12 R. N. Nayak, Y. K. Sehgal, and S. Sen, "EHV Transmission Line Capacity Enhancement through Increase in Surge Impedance Loading Level," in *IEEE Power India Conf.*, New Delhi, India, Apr. 2006.

2.13 J. R. Daconti and D. C. Lawry, "Increasing Power Transfer Capability of Existing Transmission Lines," *proc. IEEE/PES T&D Conf. and Expo.*, Dallas, USA, Sep. 2003, pp. 1004-1009.

2.14 D. F. Shankle, "Incremental Voltage Uprating of Transmission Lines," *IEEE Trans. Power App. Syst.*, vol. PAS-90, no. 4, pp. 1791-1795, Jul. 1971.

2.15 *Insulation Co-ordination - Part 1: Definitions, Principles and Rules,* International Electrotechnical Commission Standard IEC 60071-1, 2006.

2.16 *Overhead Line Clearances*, Energy Network Association, London, UK, Technical Specification 43-8, Issue 3, 2004.

2.17 *Overhead Electrical Lines Exceeding AC 45kV – Part 1: General Requirements – Common Specifications*, British Standard BSEN 50341-1, 2001.

2.18 *Overhead Electrical Lines Exceeding AC 45kV – Part 3: Set of National Normative Aspects*, British Standard BSEN 50341-3, 2001.

2.19 *Insulation Co-ordination - Part 2: Application Guide*, International

Electrotechnical Commission Standard IEC 60071-2, 1997.

2.20 M. G. Comber and L. E. Zaffanella, "Audible Noise," in *Transmission Line Reference Book 345kV and Above*, Palo Alto, CA, USA : EPRI, 1975, ch. 6, pp. 192-238.

2.21 ENSG, "Our Electricity Transmission Network: A Vision for 2020," Electricity Network Strategy Group, UK, Rep. ENSRG 2009-026, Jul. 2009.

2.22 T. Kavanagh and O. Armstrong, "An Evaluation of High Temperature Low Sag Conductors for Uprating the 220kV Transmission Network in Ireland," in *45th Int. Univ. Power Eng. Conf.*, Cardiff, UK, Aug.-Sep. 2010.

2.23 *Guide for Upgrading RUS Transmission Lines*, Rural Utilities Service, US Dept. of Agriculture, RUS Bulletin 1724E-203, Dec. 1994.

2.24 R. Baldick and R. P. O'Neill, "Estimates of Comparative Costs for Uprating Transmission Capacity," *IEEE Trans. Power Del.*, vol. 24, no. 2, pp. 961-969, Apr. 2009.

2.25 S. J. Piernot and J. Leahy, "Maximize the Capacity of Your Transmission Lines," *proc. IEEE/PES T&D Conf. and Expo.*, Atlanta, USA, Oct.-Nov. 2001, vol. 1, pp. 391-396.

2.26 M. J. Tunstall, S. P. Hoffmann, N. S. Derbyshire, and M. J. Pyke, "Maximising the Ratings of National Grid's Existing Transmission Lines using High Temperature, Low Sag Conductor," *CIGRE Session*, Paper 22-202, Paris, 2000.

2.27 R. Stephen and D. Muftic, "Determination of the Thermal Rating and Uprating Methods for Existing Lines," *CIGRE Session*, Paper 22-305, Paris, 2000.

2.28 A. L. Tukachinsky, "Uprating of Power Transmission Lines in Israel Electric Corp.," *proc. The 21st IEEE Conv. of the Elec. and Electron. Engineers in Israel*, Tel-Aviv, Israel, Apr. 2000, pp. 314-317.

2.29 M. Broschat, and R. Clayton, "Compaction Techniques Applied to Subtransmission Line Uprating 41.6kV to 115kV," *IEEE Trans. Power App. Syst.*, vol. PAS-100, no. 4, pp. 1959-1965, Apr. 1981.

2.30 T. Kikuchi, W. Oba, Y. Kojima, Y. Asano, and S. Matsui, "Compact Transmission Lines for Increasing Voltage while Keeping Existing Equipment Intact," *CIGRE Session*, Paper 22/33/36-03, Paris, 1998.

2.31 R. Stephen, "Description and Evaluation of Options Relating to Uprating of Overhead Transmission Lines," *CIGRE Session*, Paper B2-201, Paris, 2004.

2.32 S. P. Hoffmann and A. M. Clark, "The Approach to Thermal Uprating of Transmission Lines in the UK," *CIGRE Session*, Paper B2-317, Paris, 2004.

2.33 E. C. (Rusty) Bascom III et al., "Transmission Systems," in *Standard Handbook for Electrical Engineers*, 15th Edition, D. G. Fink and H. W. Beaty, Eds. New York, USA : McGraw-Hill, 2006, sec. 14.

2.34 R. Bhattarai, A. Haddad, H. Griffiths, and N. Harid, "Voltage Uprating of Overhead Transmission Lines," in *45th Int. Univ. Power Eng. Conf.*, Cardiff, UK, Aug.-Sep. 2010.

2.35 *Conductors for the Uprating of Overhead Lines*, CIGRE WG B2.12, Brochure 244, Apr. 2004.

2.36 J. M. Ferguson and R. R. Gibbon, "Overhead Transmission Lines – Refurbishment and Developments," *IEE Power Eng. Journal*, vol. 8, no. 3, pp. 109-118, Jun. 1994.

2.37 *Considerations Relating to the Use of High Temperature Conductors*, CIGRE WG B2.03, B2.12, B2.11, Brochure 331, 2007.

2.38 I. T. Domingues, J. C. R. Lopes, R. Roquelane, S. Cabral, and S. Ueda, "Uprating of Transmission Lines – Reconductoring ACSR by Conductors Thermo-resistant TACSR and TACIR (Invariable)," in *IEEE/PES T&D Conf. and Expo: Latin America*, Sao Paulo, Brazil, Nov. 2004.

2.39 I. Zamora *et al.*, "High-temperature Conductors: A Solution in the Uprating of Overhead Transmission Lines," *proc. IEEE Porto Power Tech Conf.*, Porto, Portugal, Sep. 2001.

2.40 E. Mateescu, D. Marginean, G. Gheorghita, E. Dragan, St. I. A. Gal and C. Matea, "Uprating a 220kV Double Circuit Transmission Line in Romania; Study of the Possible Solutions, Technical and Economic Comparison," *proc. IEEE Bucharest Power Tech Conf.*, Bucharest, Romania, Jun.-Jul. 2009.

2.41 F. R. Thrash Jr., "ACSS/TW – An Improved Conductor for Upgrading Existing Lines or New Construction," *proc. IEEE T&D Conf.*, New Orleans, USA, Apr. 1999, vol. 2, pp. 852-857.

2.42 *IEEE standard for Calculating the Current-Temperature of Bare Overhead Conductors*, IEEE Standard 738, 2006.

2.43 *Thermal Behaviour of Overhead Conductors*, CIGRE WG 22.12, Brochure 207, 2002.

2.44 M. L. Lu, G. Pfrimmer, and Z. Kieloch, "Upgrading and Existing 138kV Transmission Line in Manitoba," in *IEEE/PES General Meeting*, Montreal, Canada, Jun. 2006.

2.45 B. Cauzillo, L. Paris, and G. Pirovano, "Ampacity Assessment of Overhead Line Conductors as a Compromise Between Safety and Deregulated Market Requirements," *CIGRE Session*, Paper 22-206, Paris, 2002.

2.46 *Probabilistic Determination of Conductor Current Ratings*, WG 22.12, Electra No. 164, Feb. 1996.

2.47 C. F. Price and R. R. Gibbon, "Statistical Approach to Thermal Rating of Overhead Lines for Power Transmission and Distribution," *IEE Proc. C Generation, Transmission and Distribution*, vol. 130, no. 5, pp. 245-256, Sep.

1983.

2.48 F. Soto, D. Alvira, L. Martin, J. Latorre, J. Lumbreras, and M. Wagensberg, "Increasing the Capacity of Overhead Lines in the 400kV Spanish Transmission Network: Real Time Thermal Ratings," *CIGRE Session*, Paper 22-211, Paris, 1998.

2.49 P. M. Callahan and D. A. Douglass, "An experimental Evaluation of a Thermal Line Uprating by Conductor Temperature and Weather Monitoring," *IEEE Trans. Power Del.*, vol. 3, no. 4, pp. 1960-1967, Oct. 1988.

2.50 R. J. Carrington, "New Technologies for Transmission Line Uprating," *proc. IEEE 8th Int. Conf. on T&D Construction, Operation and Live-Line Maintenance*, Orlando, USA, Apr. 1998, pp. 311-318.

2.51 T. O. Seppa *et al.*, "Use of On-line Tension Monitoring for Real-time Thermal Ratings, Ice Loads and Other Environmental Effects," *CIGRE Session*, Paper 22-102, Paris, 1998.

2.52 C. Mensah-Bonsu and G. T. Heydt, "Overhead Transmission Conductor Sag: A Novel Measurement Technique and the Relation of Sag to Real Time Circuit Ratings," *Electric Power Components and Systems*, vol. 31, no. 1, pp. 61-69, 2003.

2.53 L. A. S. Pilotto, "Enhancement of Transmission Capability" Power Point Presentation in *NSF/EPRI Workshop on Urgent Opportunities for Transmission System Enhancement*, Palo Alto, CA, USA, Oct. 2001.

2.54 J. H. M. Fernandes *et al.*, "Electronorte and the Challenge of Long-distance Transmission in Brazil," *CIGRE Session*, Paper B2-111, Paris, 2008.

2.55 *National Electrical Safety Code 2007 Edition*, IEEE Standard C2-2007, 2006.

2.56 *Insulation Co-ordination - Part 4: Computational Guide to Insulation Co-ordination and Modelling of Electrical Networks*, International Electrotechnical Commission Standard IEC 60071-4, 2004.

2.57 *Overhead Electrical Lines Exceeding AC 1kV up to and Including AC 45kV*, British Standard BSEN 50423, 2005.

2.58 *Relevant Electrical Standards*, Issue 1, National Grid, Warwick, UK, Jan. 2006.

2.59 T. M. Sekili and G. U. Martinez "Uprating Double-Circuit Transmission Lines 115kV to 230kV," in *Sargent & Lundy Transmission & Substation Conf.*, Chicago, IL, USA, Nov. 1982.

2.60 K. D. Simpson "Uprating Transmission Lines," in *Sargent & Lundy Transmission & Substation Conf.*, Chicago, IL, USA, Nov. 1990.

2.61 M. Broschat, "Transmission Line Uprating 115kV to 230kV – Report on Operating Performance," *IEEE Trans. Power App. Syst.*, vol. PAS-91, no. 2, pp. 545-548, Mar. 1972.

2.62 O. L. S. de Paiva and M. S. Filho, "Reviewing 10 Years of Operating Experience with Composite Insulators at CHESF," in *World Congress & Exhibition on Insulators, Arresters & Bushings*, Crete, Greece, May 2009.

2.63 A. Nourai, A. J. F. Keri, and R. Marsico, "Upgrade-Loops: Apparatus and Method for Increasing Electrical Clearances of Energized Conductors," *IEEE Trans. Power Del.*, vol. 12, no. 4, pp. 1836-1841, Oct. 1997.

2.64 *Selection and Dimensioning of High Voltage Insulators Intended for Use in Polluted Conditions*, International Electrotechnical Commission Standard IEC60815, 2008.

2.65 C. E. Williamson, "Transmission Line Developments up to 150 kV in Eastern Australia," *proc. Int. Conf. on Overhead Line Design and Construction: Theory and Practice*, London, UK, Nov. 1988, pp. 173-177.

2.66 S. N. Tiwari, G. K. Singh, and A. S. Bin Saroor, "Multiphase Power Transmission Research – A Survey," *Electric Power System Research*, vol. 24, no. 3, pp. 207-215, Sep. 1992.

2.67 W. C. Guyker and D. F. Shankle, "138-kV Six-Phase Uprating of a 138-kV Double-Circuit Line," *IEEE Trans. Power App. Syst.*, vol. PAS-104, no. 9, pp. 2547-2554, Sep. 1985.

2.68 S. C. Nogales *et al.*, "HTLS and HVDC Solutions for Overhead Lines Uprating," in *11th Spanish-Portuguese Conf. on Elect. Eng.*, Zaragoza, Spain, Jul. 2009.

2.69 A. Clerici, L. Paris, and P. Danfors, "HVDC Conversion of HVAC Lines to Provide Substantial Power Upgrading," *IEEE Trans. Power Del.*, vol. 6, no. 1, pp. 324-333, Jan. 1991.

2.70 J. Lundkvist, I. Gutman, and L. Weimers, "Feasibility Study for Converting 380kV AC Lines to Hybrid AC/DC Lines," in *EPRI's High-Voltage Direct Current & Flexible AC Transmission Systems Conf.*, Westminster, CO, USA, Nov. 2009.

2.71 H. Rahman and B. H. Khan, "Power Upgrading of Transmission Line by Combining AC – DC Transmission," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 459-466, Feb. 2007.

2.72 *Advice on Limiting Exposure to Electromagnetic Fields (0-300GHz)*, National Radiological Protection Board, Chilton, UK, vol. 15, no. 2, 2004.

2.73 ICNIRP, "Guidelines for Limiting Exposure to Time-varying Electric, Magnetic, and Electromagnetic Fields (Up to 300 GHz)," *Health Phys.*, vol. 74, no. 4, 1998.

2.74 S. Ninisto, "Council Recommendation of 12 July 1999 on the Limitation of Exposure of the General Public to Electromagnetic Fields (0 Hz to 300 GHz)," *Official Journal of the European Communities*, 1999/519/EC, Jul. 1999.

2.75 National Grid. *EMF's.info: Electric and Magnetic Fields* [Online]. Available: http://www.emfs.info/Related+Issues/limits/UK/

2.76 *Electric and Magnetic Fields – The Facts*, Energy Networks Association, London, UK, Jan. 2007.

2.77 F. Kiessling, D. Hussels, C. Juerdens, and J. Ruhnau, "Upgrading High-Voltage Lines to Increase their Capacity and Mitigate Environmental Impacts," *CIGRE Session*, Paper 22-208, Paris, 1998.

2.78 J. W. Simpson and V. E. Ogorodnikov, "Conversion of 115kV Lines to 230kV and Subsequent Operation at Voltages up to 262kV," *CIGRE Paper 407*, Paris, 1958.

2.79 P. S. Dean *et al.*, "Insulation Test for the Design and Uprating of Wood-Pole Transmission Lines," *IEEE Trans. Power App. Syst.*, vol. PAS-85, no. 12, pp. 1258-1267, Dec. 1966.

2.80 L. C. Weber, E. C. Glass, and G. W. Alexander, "Application of Statistical Methods in the Design and Uprating of Wood-Pole Transmission Lines," *IEEE Trans. Power App. Syst.*, vol. 84, no. 8, pp. 725-732, Aug. 1965.

2.81 PowerServe, "Proposed Lismore to Mullumbimby Electricity Network Upgrade," PowerServe Australia, Thornton, QLD, Australia, Rep. MP0048-001, Rev 2, Mar. 2008.

2.82 TransGrid Corporate Business Unit, "Annual Report 2009", TransGrid, Sydney, NSW, Australia, 2009.

2.83 TransGrid, "New Small Transmission Network Asset – Uprating of Sydney West 132kV Fault Interruption Capability", TransGrid, Sydney, NSW, Australia, Dec. 2006.

2.84 TransGrid, "New Small Transmission Network Asset – Uprating of 966 Armidale – Koolkhan 132kV Transmission Line", TransGrid, Sydney, NSW, Australia, Nov. 2005.

2.85 G. Charcosset and M. Loisel, "Uprating of a 30kV Overhead Line to 90kV," *proc. 10th Int. Conf. on Electricity Distribution*, Brighton, UK, May. 1989, vol.3, pp. 262.

2.86 I. Zamora, A. J. Mazon, R. Criado, C. Alonso, and J. R. Saenz, "Uprating using High-temperature Electrical Conductors," in *16th Int. Conf. and Exhibition on Electricity Distribution*, Amsterdam, Netherlands, Jun. 2001.

2.87 C. H. Bayfield, "Upgrading the Anglo-Scottish Interconnection," *IEE Power Eng. Journal*, vol. 8, no. 4, pp. 161-167, Aug. 1994.

2.88 A. V. Richardson, "Upgrading the Anglo-Scottish Interconnection – Keynote Address & Project Overview," *proc. IEE Colloquium on Upgrading the Anglo-Scottish Interconnector*, London, UK, Apr. 1994, pp. 1/1-1/6.

2.89 NG, "Proposed Spennymoor to Norton 400kV Overhead Line – Environmental Statement," National Grid, Warwick, UK, Jul. 2009, vol. I.

2.90 Sargent & Lundy. *Transmission Line Uprating Services and Current Projects*, Leaflet [Online]. Available: http://www.sargentlundy.com/power-delivery/line-uprate.html

CHAPTER 3

3.1 *Insulation Co-ordination - Part 1: Definitions, Principles and Rules*, International Electrotechnical Commission Standard IEC 60071-1, 2006.

3.2 *Insulation Co-ordination - Part 2: Application Guide*, International Electrotechnical Commission Standard IEC 60071-2, 1997.

3.3 *Insulation Co-ordination - Part 4: Computational Guide to Insulation Co-ordination and Modelling of Electrical Networks*, International Electrotechnical Commission Standard IEC 60071-4, 2004.

3.4 *Overhead Electrical Lines – Calculation of the Electrical Component of Distance between Live Parts and Obstacles – Method of Calculation*, International Electrotechnical Commission Standard IEC 61865, 2001.

3.5 *Overhead Electrical Lines Exceeding AC 45kV – Part 1: General Requirements – Common Specifications*, British Standard BSEN 50341-1, 2001.

3.6 *Overhead Electrical Lines Exceeding AC 45kV – Part 3: Set of National Normative Aspects*, British Standard BSEN 50341-3, 2001.

3.7 *Overhead Electrical Lines Exceeding AC 1kV up to and Including AC 45kV*, British Standard BSEN 50423, 2005.

3.8 *Live Working – Minimum Approach Distances for A.C. Systems in the Voltage Range 72.5kV to 800kV – A Method of Calculation*, International Electrotechnical Commission Standard IEC 61472, 2004.

3.9 *Selection and Dimensioning of High Voltage Insulators Intended for Use in Polluted Conditions – Part 1: Definitions, Information and General Principles*, International Electrotechnical Commission Standard IEC 60815-1, 2008.

3.10 *Selection and Dimensioning of High Voltage Insulators Intended for Use in Polluted Conditions – Part 2: Ceramic and Glass Insulators for A.C. Systems*, International Electrotechnical Commission Standard IEC 60815-2, 2008.

3.11 J. D. Brown, J. J. LaForest, K.W. Priest, C. J. Truax, and D. D. Wilson, "Insulation Design – General Concepts," in *Transmission Line Reference Book 345kV and Above*, Palo Alto, CA, USA : EPRI, 1975, ch. 9, pp. 281-295.

3.12 UHV AC Transmission Committee – Power System WG, "Characteristics of UHV AC Transmission System," CRIEPI Report, Japan, 1982.

3.13 L. Paris and R. Cortina, "Switching and Lightning Impulse Discharge

Characteristics of Large Air Gaps and Long Insulator Strings," *IEEE Trans. Power App. Syst.*, vol. PAS-87, no. 4, pp. 947-957, Apr. 1968.

3.14 T. Udo, "Switching Surge and Impulse Sparkover Characteristics of Large Gap Spacings and Long Insulator Strings," *IEEE Trans. Power App. Syst.*, vol. 84, no. 4, pp. 304-309, Apr. 1965.

3.15 L. Paris, "Influence of Air Gap Characteristics on Line-to-Ground Switching Surge Strength," *IEEE Trans. Power App. Syst.*, vol. PAS-86, no. 8, pp. 936-947, Aug. 1967.

3.16 Y. Watanabe, "Switching Surge Flashover Characteristics of Extremely Long Air Gaps," *IEEE Trans. Power App. Syst.*, vol. PAS-86, no. 8, pp. 933-936, Aug. 1967.

3.17 G. Carrara and L. Thione, "Switching Surge Strength of Large Air Gaps : A Physical Approach," *IEEE Trans. Power App. Syst.*, vol. PAS-95, no. 2, pp. 512-524, Mar. 1976.

3.18 S. Venkatesan, R. Rasheddin, R. Bhattarai, A. Haddad, N. Harid, and H. Griffiths, "Significance of Switching Impulse Breakdown Voltage Characteristics in Voltage Uprating," *proc. XVII Int. Conf. on Gas Discharge and Their Applicat.*, Cardiff, UK, Sep. 2008, pp. 353-356.

CHAPTER 4

4.1 *Electrical Parameters and Impedance Characteristics of Plant, Lines and Cables*, National Grid, Warwick, UK, Tech. Guidance Note TGN(E)166, Issue 2, Feb. 2002.

4.2 M. J. Tunstall, S. P. Hoffmann, N. S. Derbyshire, and M. J. Pyke, "Maximising the Ratings of National Grid's Existing Transmission Lines using High Temperature, Low Sag Conductor," *CIGRE Session*, Paper 22-202, Paris, 2000.

4.3 *Line Profile – 275kV Overhead Transmission Line, XL Route*, National Grid, Warwick, UK, Nov. 2007.

4.4 *Conductors for Overhead Lines – Round Wire Concentric Lay Stranded Conductors*, British Standard BSEN 50182, 2001.

4.5 *Specification for Aluminium Conductors and Aluminium Conductors, Steel-Reinforced – For Overhead Power Transmission - Part 2: Aluminium Conductors, Steel-Reinforced*, British Standard BS 215-2, 1970.

4.6 *Design Document for 275kV Suspension Insulator Set, L3 Towers*, National Grid, Warwick, UK, Oct. 2007.

4.7 *Insulator and Conductor Fittings for Overhead Power Lines – Part 2: Specification for a Range of Insulator Fittings*, British Standard BS 3288-2, 2009.

4.8 *Insulators and Fittings for 275kV Lines*, Energy Network Association, London, UK, Technical Specification 43-115, Issue 1, 1997.

4.9 *Overhead Electrical Lines Exceeding AC 45kV – Part 1: General Requirements – Common Specifications*, British Standard BSEN 50341-1, 2001.

4.10 *Overhead Electrical Lines Exceeding AC 45kV – Part 3: Set of National Normative Aspects*, British Standard BSEN 50341-3, 2001.

4.11 *Guidelines for Increased Utilization of Existing Overhead Transmission Lines*, CIGRE WG B2.13, Brochure 353, Aug. 2008.

4.12 R. Rashedin, H. Griffiths, N. Harid, and A. Haddad, "Uprating the Electrical Capacity of an Existing Transmission Line – 275kV to 400kV," in *16th Int. Symp. on High Voltage Eng.*, Cape Town, South Africa, Aug. 2009.

4.13 *Selection and Dimensioning of High Voltage Insulators Intended for Use in Polluted Conditions – Part 1: Definitions, Information and General Principles*, International Electrotechnical Commission Standard IEC 60815-1, 2008.

4.14 R. Hackam, "Outdoor High Voltage Polymeric Insulators," *proc. Int. Symp. on Electrical Insulating Materials*, Toyohashi, Japan, Sep. 1998.

4.15 S. M. Rowland, Y. Xiong, J. Robertson, and S. Hoffmann, "Aging of Silicone Rubber Composite Insulators on 400kV Transmission Lines," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 14, no. 1, pp. 130-136, Feb. 2007.

4.16 Liling Orient Power Co. Ltd. (China). *Composite Insulator* [Online]. Available: FTP: http://www.powerinsulator.com/list.asp?id=201 File: polymer/silicone rubber long rod (suspension) insulator. pdf

4.17 *HVCE – High Voltage Creepage Extenders – A Remedy for Pollution Flashover of Insulators*, Tyco Electronics Energy Division, Ottobrunn/Munich, Germany, 2002.

4.18 R. S. Gorur, "High-Voltage Transmission," in *The Electrical Engineering Handbook*, W. K. Chen, Ed. London, UK : Elsevier Acad. Press, 2005, ch. 5, sec. VI, pp. 737-748.

4.19 *Insulation Co-ordination - Part 2: Application Guide*, International Electrotechnical Commission Standard IEC 60071-2, 1997.

4.20 *IEEE Guide for Improving the Lightning Performance of Transmission Lines*, IEEE Standard 1243, 1997.

4.21 *Controlled Switching – Buyer's & Application Guide,* 3rd ed., ABB, Ludvika, Sweden, 2009-04.

4.22 M. Sanaye-Pasand, M. R. Dadashzadeh, and M. Khodayar, "Limitation of Transmission Line Switching Overvoltages using Switchsync Relays," in *Int. Conf. on Power System Transients*, Montreal, Canada, Jun. 2005.

4.23 K. Froehlich *et al.*, "Controlled Closing on Shunt Reactor Compensated Transmission Lines – Part I: Closing Controlled Device Development," *IEEE Trans. Power Del.*, vol. 12, no. 2, pp. 734-740, Apr. 1997.

4.24 H. Seyedi, M. Sanaye-Pasand, and M. R. Dadashzadeh, "Application of Transmission Line Surge Arresters to Reduce Switching Overvoltages," in *Int. Conf. on Power System Transients*, Montreal, Canada, Jun. 2005.

4.25 R. Bhattarai, A. Haddad, H. Griffiths, and N. Harid, "Voltage Uprating of Overhead Transmission Lines," in *45th Int. Univ. Power Eng. Conf.*, Cardiff, UK, Aug.-Sep. 2010.

CHAPTER 5

5.1 S. Sadovic, R. Joulie, S. Tartier, and E. Brocard, "Use of Line Surge Arresters for the Improvement of the Lightning Performance of 63kV and 90kV Shielded and Unshielded Transmission Lines," *IEEE Trans. Power Del.*, vol. 12, no. 3, pp. 1232-1240, Jul. 1997.

5.2 J. A. Martinez and F. Castro-Aranda, "Lightning Performance Analysis of Overhead Transmission Lines using the EMTP," *IEEE Trans. Power Del.*, vol. 20, no. 3, pp. 2200-2210, Jul. 2005.

5.3 L. Stenstrom and M. Mobedjina, "Limitation of Switching Overvoltages by use of Transmission Line Surge Arresters," in *CIGRE SC33 Int. Conf.*, Zagreb, Croatia, 1998.

5.4 H. Seyedi, M. Sanaye-Pasand, and M. R. Dadashzadeh, "Application of Transmission Line Surge Arresters to Reduce Switching Overvoltages," in *Int. Conf. on Power System Transients*, Montreal, Canada, Jun. 2005.

5.5 K. Jeong-Boo, S. Eung-Bo, and S. Jeong-Woon, "Switching Overvoltage Analysis and Air Clearance Design on the KEPCO 765kV Double Circuit Transmission System," *IEEE Trans. Power Del.*, vol. 15, no. 1, pp. 381-386, Jan. 2000.

5.6 J. A. Tarchini and W. Gimenez, "Line Surge Arrester Selection to Improve Lightning Performance of Transmission Lines," *proc. IEEE Bologna PowerTech Conf.*, Bologna, Italy, Jun. 2003.

5.7 S. Venkatesan, A. Haddad, H. Griffiths, N. Harid, and M. Albano, "Reducing Air Clearance Requirements for Voltage Uprating of Overhead Line by use of Line Surge Arresters," *proc. IEEE Conf. on Electrical Insulation and Dielectric Phenomena*, Virginia Beach, USA, Oct. 2009.

5.8 *Electromagnetic Transients Program (EMTP) Theory Book*, Bonneville Power Administration, Portland, USA, 1986.

5.9 J. R. Marti, "Accurate Modelling of Frequency-Dependent Transmission Lines in Electromagnetic Transient Simulations," *IEEE Trans. Power App. Syst.*, vol.

PAS-101, no. 1, pp. 147-157, Jan. 1982.

5.10 *High Voltage Surge Arresters – Buyer's Guide,* 5.1 ed., ABB, Ludvika, Sweden, 2007-04.

5.11 *Insulation Co-ordination - Part 2: Application Guide,* International Electrotechnical Commission Standard IEC 60071-2, 1997.

5.12 *Insulation Co-ordination - Part 1: Definitions, Principles and Rules*, International Electrotechnical Commission Standard IEC 60071-1, 2006.

5.13 *IEEE Guide for Improving the Lightning Performance of Transmission Lines*, IEEE Standard 1243, 1997.

5.14 *Guide to Procedures for Estimating the Lightning Performance of Transmission Lines*, CIGRE WG 33.01, Brochure 63, Oct. 1991.

5.15 *Handbook for Improving Overhead Transmission Line Lightning Performance*, Document no. 1002019, EPRI, Palo Alto, CA, USA, Dec. 2004.

5.16 *SIGMA Slp – Version 2.1 : Software for the Determination of Transmission and Distribution Line Electrical Performance (User Manual)*, Sadovic Consultant, Boulogne, France, 2005.

5.17 TFlash Users' Guide, EPRI, Palo Alto, CA, USA.

5.18 I. S. Grant *et al.*, "A Simplified Method for Estimating Lightning Performance of Transmission Lines," *IEEE Trans. Power App. Syst.*, vol. PAS-104, no. 4, pp. 918-932, Jul. 1985.

5.19 J. T. Whitehead *et al.*, "Estimating Lightning Performance of Transmission Lines II – Updates to Analytical Models," *IEEE Trans. Power Del.*, vol. 8, no. 3, pp. 1254-1267, Jul. 1993.

5.20 A. F. Imece *et al.*, "Modeling Guidelines for Fast Front Transients," *IEEE Trans. Power Del.*, vol. 11, no. 1, pp. 493-506, Jan. 1996.

5.21 J. A. Martinez-Velasco and F. Castro-Aranda, "Modeling of Overhead Transmission Lines for Lightning Studies," in *Int. Conf. on Power System Transients*, Montreal, Canada, Jun. 2005.

5.22 J. A. Martinez and F. Castro-Aranda, "Modeling Overhead Transmission Lines for Line Arrester Studies," in *IEEE Power Engineering Society General Meeting*, Colorado, USA, Jun. 2004.

5.23 T. Hara and O. Yamamoto, "Modelling of a Transmission Tower for Lightning-Surge Analysis," *IEE Proc. Generation, Transmission & Distribution*, vol.143, no.3, pp.283-289, May 1996

5.24 A. J. Eriksson and K. H. Weck, "Simplified Procedures for Determining Representative Substation Impinging Lightning Overvoltages," *CIGRE Session*, Paper 33-16, Paris, 1998.

5.25 U. Savadamuthu, K. Udayakumar, and V. Jayashankar, "Modified Disruptive Effect Method as a Measure of Insulation Strength for Non-standard Lightning Waveforms," *IEEE Trans. Power Del.*, vol. 17, no. 2, pp. 510-515, Apr. 2002.

5.26 P. Chowdhuri *et al.*, "Parameters of Lightning Strokes : A Review," *IEEE Trans. Power Del.*, vol. 20, no. 1, pp. 346-358, Jan. 2005.

CHAPTER 6

6.1 *High Voltage Surge Arresters – Buyer's Guide,* 5.1 ed., ABB, Ludvika, Sweden, 2007-04.

6.2 *Guide to Procedures for Estimating the Lightning Performance of Transmission Lines*, CIGRE WG 33.01, Brochure 63, Oct. 1991.

6.3 P. Chowdhuri *et al.*, "Parameters of Lightning Strokes : A Review," *IEEE Trans. Power Del.*, vol. 20, no. 1, pp. 346-358, Jan. 2005.

6.4 T. Short, "Application of the IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines (Std. 1410-1997)," prepared for *IEEE PES T&D Conf.*, New Orleans, USA, Apr. 1999.

6.5 *Protection Against Lightning - Part 2: Risk Management*, British Standard BSEN 62305-2, 2006.

6.6 Liling Orient Power Co. Ltd. (China). *Composite Insulator* [Online]. Available: FTP: http://www.powerinsulator.com/list.asp?id=201 File: polymer/silicone rubber long rod (suspension) insulator. pdf

6.7 *Handbook for Improving Overhead Transmission Line Lightning Performance*, Document no. 1002019, EPRI, Palo Alto, CA, USA, Dec. 2004.

6.8 *Transmission Line Surge Arrester Impulse Energy Testing*, Document no. 1000461, EPRI, Palo Alto, CA, USA.

6.9 J. A. Tarchini and W. Gimenez, "Line Surge Arrester Selection to Improve Lightning Performance of Transmission Lines," *proc. IEEE Bologna PowerTech Conf.*, Bologna, Italy, Jun. 2003.

6.10 S. Sadovic, R. Joulie, S. Tartier, and E. Brocard, "Use of Line Surge Arresters for the Improvement of the Lightning Performance of 63kV and 90kV Shielded and Unshielded Transmission Lines," *IEEE Trans. Power Del.*, vol. 12, no. 3, pp. 1232-1240, Jul. 1997.

6.11 *Surge Arresters - Part 4: Metal-Oxide Surge Arresters without Gap for A.C. Systems*, International Electrotechnical Commission Standard IEC 60099-4, 2004.

7.1 Independent Advisory Group on Non-ionising Radiation, "Power Frequency Electromagnetic Fields, Melatonin and the Risk of Breast Cancer," Health Protection Agency, UK, Rep. RCE-1, Feb. 2006.

7.2 *Establishing a Dialogue on Risk from Electromagnetic Fields*, Dept. of Protection of the Human Environment, World Health Organization, Geneva, Switzerland, 2002.

7.3 National Grid. *EMF's.info: Electric and Magnetic Fields* [Online]. Available: http://www.emfs.info/Related+Issues/SAGE/first/corridorwidth.htm

7.4 ICNIRP, "Guidelines for Limiting Exposure to Time-varying Electric, Magnetic, and Electromagnetic Fields (Up to 300 GHz)," *Health Phys.*, vol. 74, no. 4, 1998.

7.5 *IEEE Standard Procedures for Measurement of Power Frequency Electric and Magnetic Fields from AC Power Lines*, IEEE Standard 644-1994, 1995.

7.6 *Advice on Limiting Exposure to Electromagnetic Fields (0 - 300 GHz)*, National Radiological Protection Board, Oxfordshire, UK, vol. 15, no. 2, 2004.

7.7 SAGE, "Supporting Papers to the First Interim Assessment: Power Lines & Property, Wiring in Homes and Electrical Equipment in Homes," R. K. Partnership Ltd., Castle Cary, UK, Apr. 2007.

7.8 *Government Response to the Stakeholder Advisory Group on Extremely Low Frequency Electric and Magnetic Fields (ELF EMFs) (SAGE) Recommendations*, H M Government, UK, Oct. 2009. Published online: http://webarchive.nationalarchives.gov.uk/+/www.dh.gov.uk/en/Publichealth/Healthprotection/DH_4089500.

7.9 National Grid. *EMF's.info: Electric and Magnetic Fields* [Online]. Available: http://www.emfs.info/Related+Issues/limits/UK/

7.10 *Electric and Magnetic Fields – The Facts*, Energy Networks Association, London, UK, Jan. 2007.

7.11 *Electrical Parameters and Impedance Characteristics of Plant, Lines and Cables*, National Grid, Warwick, UK, Tech. Guidance Note TGN(E)166, Issue 2, Feb. 2002.

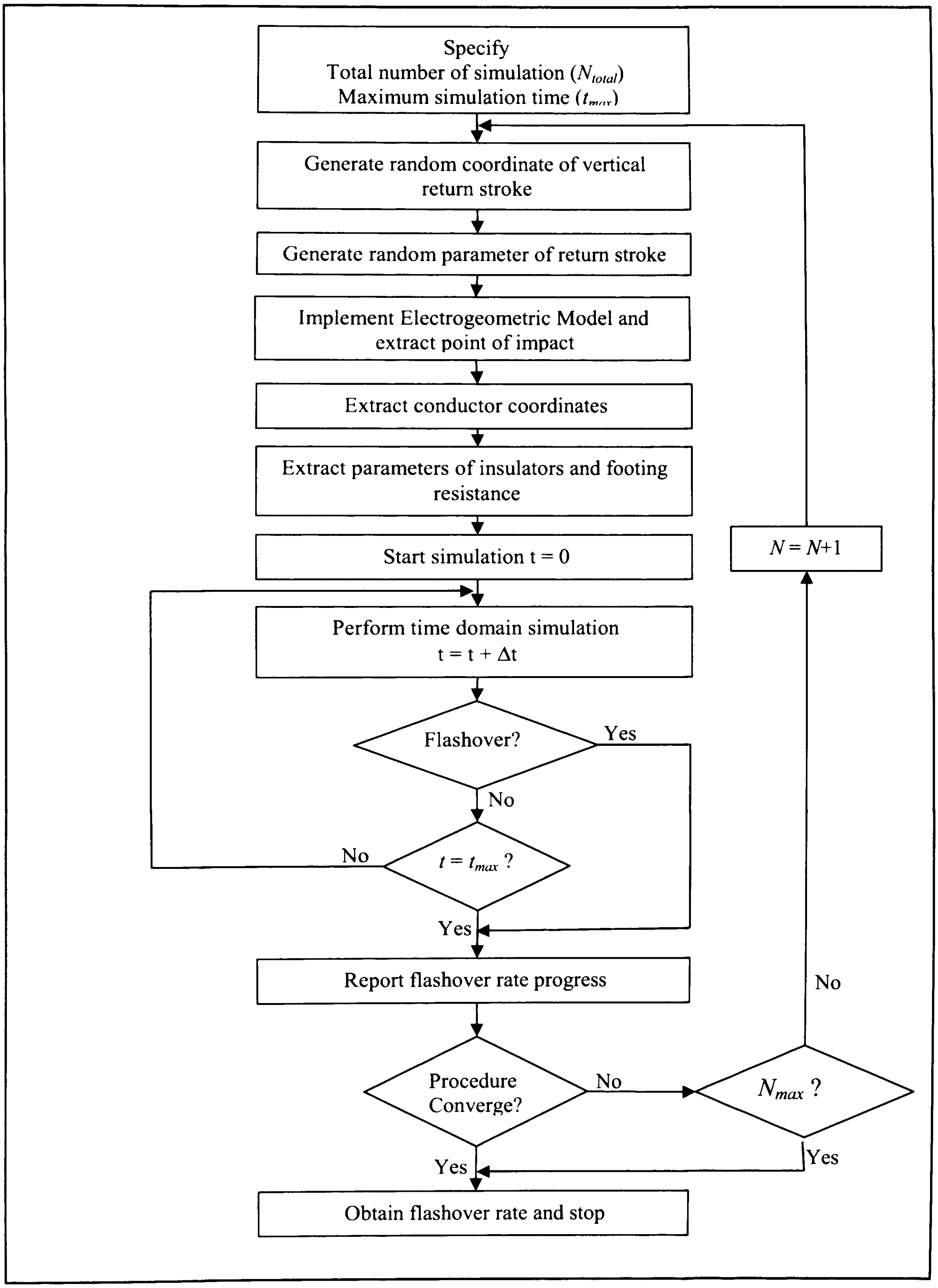
7.12 M. Albano, "Manuale Prglinea3D (Italian Version)," 2006.

7.13 M. Albano, R. Benato, and R. Turi, "Predictive Analysis of Environmental Magnetic Fields Generated by Multiple Power Lines," *proc. IEEE Bologna PowerTech Conf.*, Bologna, Italy, Jun. 2003.

7.14 National Grid. *EMF's.info: Electric and Magnetic Fields* [Online]. Available: http://www.emfs.info/Sources+of+EMFs/Overhead+power+lines/Factors/Current/

APPENDIX A

FLOW CHART OF MONTE CARLO SIMULATION METHOD FOR LIGHTNING PERFORMANCE



APPENDIX B

EPRI STROKE ATTRACTION MODEL DESCRIBED IN TFLASH USER GUIDE

(Ref: TFlash User Guide)

The EPRI model first calculates a stroke striking distance for the current being simulated from the formula:

$$Stroke\ Distance = 1.34\ I^{0.65}\ H^{0.6}$$

Where, H is ground intercept height

This takes into account that wires farther above the ground can accumulate more charge and connect to a downward leader at a greater distance. The channel location is then shifted in toward the line to simulate the attraction caused by the charge induced on the wires due to the downward leader. The factors in this shift are:

$$Attraction\ factor = 1 - \left(\frac{Channel\ Location}{300}\right)^{0.5}$$

$$x\ factor = \left(\frac{Channel\ Location}{300}\right)^{0.125}$$

$$nwires\ factor = \left(\frac{NWires}{15}\right)^{0.25}$$

$$maxheight\ factor = \left(\frac{MaxHeight}{100}\right)^{0.25}$$

$$current\ factor = 1 - \left(\frac{I}{300}\right)^{0.5}$$

Where:

Channel Location = the original X-coordinate of the channel

Nwires = the number of wires on the tower

MaxHeight = the highest point on the tower

I = the stroke current

ShiftedChannel = ChannelLocation × (1-(xfactor × nwiresfactor × maxheightfactor × currentfactor × attraction factor))

The intersection of the shifted channel with a curve that is the StrokeDistance above and beyond the outside tower wires in the right of way is calculated. The closest wire to this intersection point is then found.

Next the ground intercept height is calculated. The ground slope and obstruction locations are used to determine the height of the ground at the shifted channel location. Then the equations below are used to calculate the intercept height above that point.

If the tower maximum height is below 40m

$R_g = 3.6 + 1.7 \log (43 - height)$

else

$R_g = 5.5$

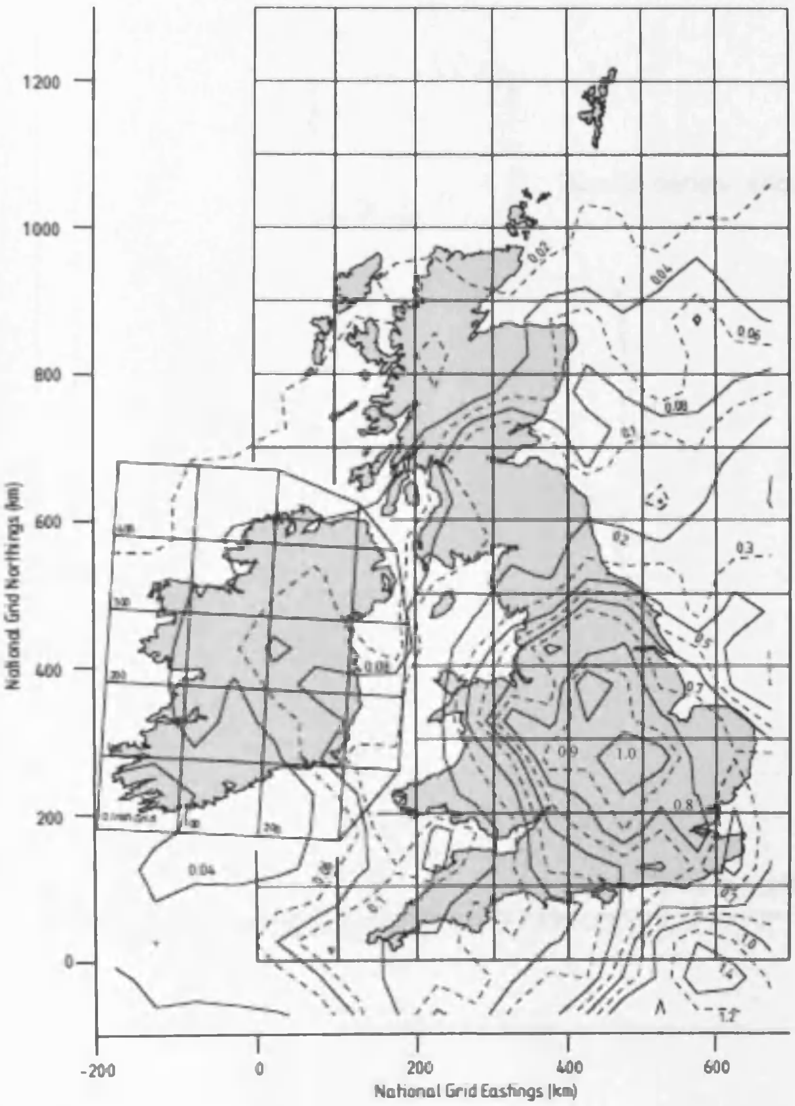
Then the ground intercept height is:

$$ground\ strk\ ht = \frac{R_g}{10} \times Stroke\ Distance$$

If this is above the height for the wire intercept found above the stroke is assumed to strike the ground instead of the wire.

APPENDIX C

LIGHTNING FLASH DENSITY TO GROUND (NG) PER SQUARE KILOMETRE PER YEAR FOR THE BRITISH ISLES (BSEN 62305-2)



NOTE 1 This lightning density map was compiled by E.A. Technology Ltd. from data accumulated over 10 years

NOTE 2 A linear interpolation should be used to determine the value of the lightning flash density, N_g, for a location between two contour lines.

APPENDIX D

CONDUCTOR COORDINATES OF OVERHEAD LINES: (WITH REFERENCE TO TABLE D1) [REF: NATIONAL GRID]

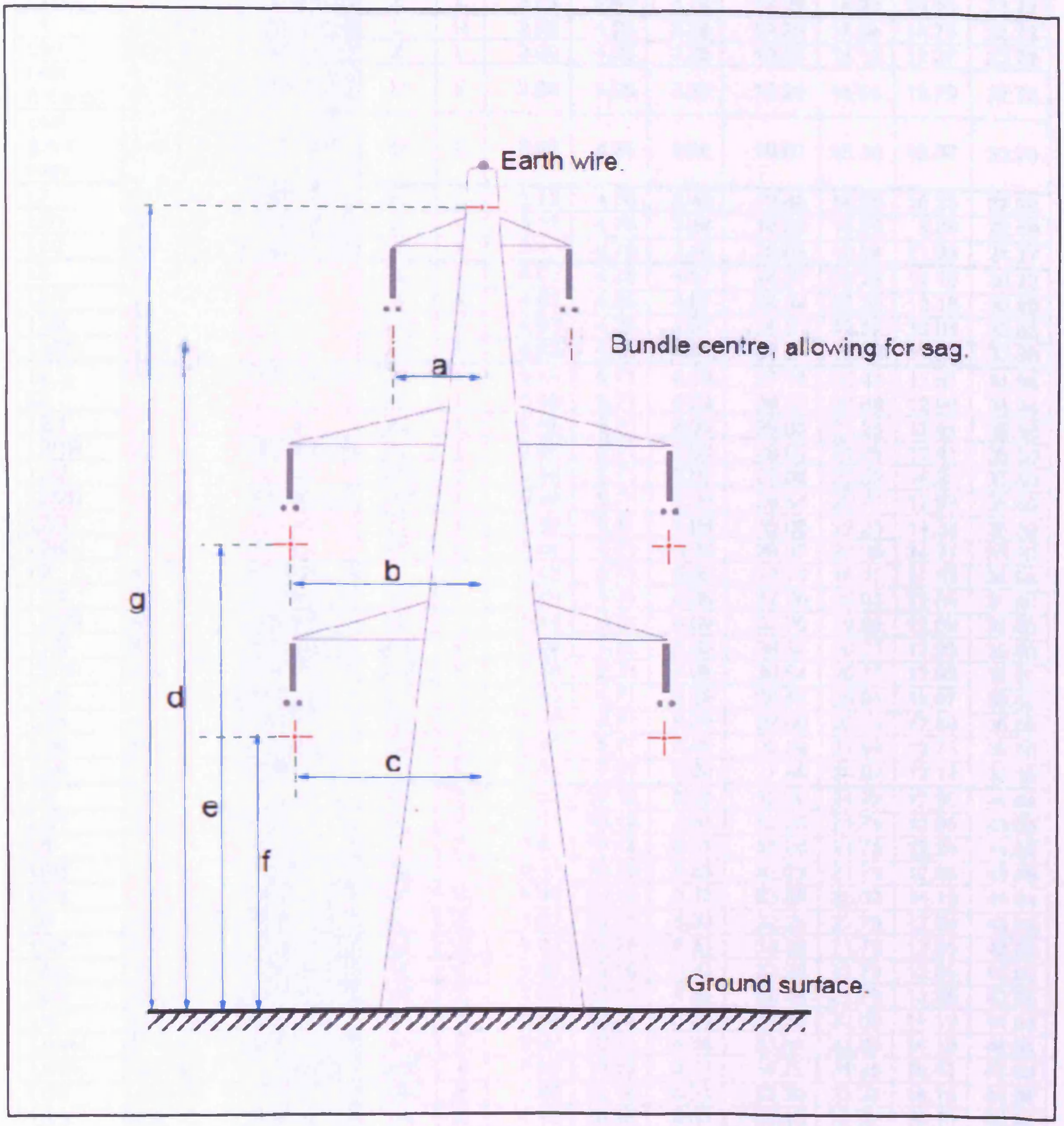


TABLE D1: CONDUCTOR COORDINATES (INCLUDING SAG) OF OVERHEAD LINE DESIGNS (REF: NATIONAL GRID)

Tower design	Operating Voltage	Insulation Voltage	ϕ	E	a	b	c	d	e	f	g
L132	132 kV	132 kV	Z	L	3.74	4.65	3.74	18.26	14.22	10.56	22.78
L4	132 kV	132 kV	L	H	2.80	4.20	3.20	18.29	14.54	10.79	22.73
L4/1	132 kV	132 kV	Z	L	2.80	4.20	3.20	19.87	16.12	12.37	23.79
L4M (L4 sag)	132 kV	132 kV	U	K	2.80	4.20	3.20	18.29	14.54	10.79	22.73
L4M (L4/1 sag)	132 kV	132 kV	U	K	2.80	4.20	3.20	19.87	16.12	12.37	23.79
L7	132 kV	132 kV	2L	L	3.12	4.70	3.48	18.48	14.06	10.35	22.59
L7/1	132 kV	132 kV	Z	L	3.12	4.70	3.48	18.02	13.60	9.89	22.59
L7/2	132 kV	132 kV	2Z	L	3.12	4.70	3.48	20.06	15.64	11.93	24.27
L3	275 kV	275 kV	2L	L	4.03	4.26	4.57	24.37	18.28	12.19	30.22
L3/1	275 kV	275 kV	A	K	4.03	4.26	4.57	24.34	18.25	12.16	30.88
L3/2	275 kV	275 kV	2U	K	4.03	4.26	4.57	25.21	19.12	13.03	30.88
L3/2R	275 kV	275 kV	2U	K	4.03	4.26	4.57	25.21	19.12	13.03	30.88
L2	132 kV	132 kV	2Z	L	5.48	5.71	6.09	27.18	19.41	11.57	34.94
L2	275 kV	275 kV	2Z	L	5.48	5.71	6.09	28.57	20.80	12.96	34.94
L2/1	275 kV	275 kV	2C	L	5.48	5.71	6.09	29.02	21.25	13.41	35.60
L2/1R	275 kV	400 kV	2C	L	5.48	5.71	6.09	29.02	21.25	13.41	35.60
L2/2	275 kV	275 kV	2RB	K	5.48	5.71	6.09	29.86	22.09	14.25	35.60
L2/2R	275 kV	400 kV	2RB	K	5.48	5.71	6.09	28.54	20.77	12.93	35.60
L2/3	275 kV	275 kV	2T	K	5.48	5.71	6.09	30.00	22.23	14.39	35.60
L2/4	275 kV	275 kV	2S	K	5.48	5.71	6.09	29.82	22.05	14.21	35.60
L2	400 kV	400 kV	2Z	L	5.48	5.71	6.09	27.24	19.47	11.63	34.94
L2/1	400 kV	400 kV	2C	L	5.48	5.71	6.09	27.70	19.93	12.09	35.60
L2/1R	400 kV	400 kV	2C	L	5.48	5.71	6.09	27.70	19.93	12.09	35.60
L2/2	400 kV	400 kV	2RB	K	5.48	5.71	6.09	28.54	20.77	12.93	35.60
L2/2R	400 kV	400 kV	2RB	K	5.48	5.71	6.09	28.54	20.77	12.93	35.60
L2/3	400 kV	400 kV	2T	K	5.48	5.71	6.09	28.68	20.91	13.07	35.60
L2/4	400 kV	400 kV	2S	K	5.48	5.71	6.09	28.50	20.73	12.89	35.60
L2/5	400 kV	400 kV	2CP	K	5.48	5.71	6.09	29.36	21.59	13.75	35.60
L2/6	400 kV	400 kV	2M	K	5.48	5.71	6.09	27.48	20.02	12.18	35.60
L6	132 kV	400 kV	4Z	Z	6.93	10.16	8.33	32.26	21.79	12.95	44.04
L6/1	132 kV	400 kV	2Z	Z	6.93	10.16	8.33	32.26	21.79	12.95	43.09
L6	275 kV	400 kV	4Z	Z	6.93	10.16	8.33	32.26	21.79	12.95	44.04
L6/1	275 kV	400 kV	2Z	Z	6.93	10.16	8.33	32.26	21.79	12.95	43.09
L6/2	275 kV	400 kV	2A	K	6.93	10.16	8.33	33.50	23.03	14.19	44.04
L6	400 kV	400 kV	4Z	Z	6.93	10.16	8.33	32.26	21.79	12.95	43.09
L6H	400 kV	400 kV	4Z	Z	6.93	10.16	8.33	32.26	21.79	12.95	43.09
L6M	400 kV	400 kV	4Z	Z	6.93	10.16	8.33	32.26	21.79	12.95	43.09
L6/1	400 kV	400 kV	2Z	Z	6.93	10.16	8.33	32.26	21.79	12.95	43.09
L6/2	400 kV	400 kV	2A	K	6.93	10.16	8.33	33.50	23.03	14.19	44.04
L6/2R	400 kV	400 kV	2A	K	6.93	10.16	8.33	33.50	23.03	14.19	44.04
L6/3R	400 kV	400 kV	2RB	Z	6.93	10.16	8.33	34.72	24.25	15.41	43.09
L6/4	400 kV	400 kV	2RW	K	6.93	10.16	8.33	33.50	23.03	14.19	44.04
L6/5	400 kV	400 kV	3A	K	6.93	10.16	8.33	33.49	23.02	14.18	44.04
L8	132 kV	400 kV	2Z	L	5.94	8.53	6.70	30.01	20.57	12.57	39.77

Key to Conductors

H = Horse
K = Keziah
U = Upas
S = Sorbus
CP = Compact 35

L = Lynx
Z = Zebra
T = Totara
A = Araucaria

F = Fibral
C = Collybia
RB = Rubus
RW = Redwood

APPENDIX E

APPLICATION OF SURGE ARRESTERS FOR LIGHTNING PROTECTION OF 33KV WOOD POLE DISTRIBUTION LINES

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ABSTRACT

Line surge arresters may be applied in high lightning activity areas for the protection of uprated/compact lines that have a lower basic insulation level. In this paper, a lightning protection study considering the application of surge arresters was conducted on a compact 33kV overhead wood pole distribution line. Different arrester configurations and spacing were investigated in open ground and naturally shielded ground and compared with the results obtained from an unprotected line. The variation in lightning protection level due to application of surge arresters at poles with unearthed and earthed crossarm structures was examined. The surge arrester energy duties were computed statistically.

INTRODUCTION

Lightning is considered to be a major cause of supply interruption on overhead distribution lines. There are numerous methods suggested by several researchers in the past for the protection of overhead distribution lines against lightning [1-3]. Amongst those, surge arrester protection of the line is of more interest as it can protect the line from both direct strikes and induced overvoltages.

Surge arresters always act to limit the lightning overvoltage below the flashover voltage of the insulation. In this study, the protection of a three-phase, 33kV wood pole distribution line was measured in terms of its lightning performances (flashes/100km/year) using a statistical approach. For this purpose, the software package Sigma-Slp, that has been developed to determine lightning protection of distribution and transmission lines, particularly, considering application of surge arresters, was used. This software makes use of multiphase travelling wave method for the computation of electromagnetic transients along the line and Monte Carlo statistical method together with Electrogeometric Model (EGM) to determine stroke termination on the line [4].

In order to estimate the flashover rate with and without surge arresters, statistical stroke analyses were carried out with different amplitudes of injected strike current. Two different cases were considered: the line in open ground and in naturally shielded ground. This study also aims to show the improvement in lightning protection level due to crossarm earthing at the pole where arresters are connected. To demonstrate the line arrester's energy capability, its energy duty was computed statistically for appropriate arrester configurations and presented in terms of cumulative frequency distribution.

SIMULATED LINE MODEL

The simulated line has a construction with all the specifications of 33kV overhead power lines from Scottish Power L20 document [5]. It considers a three-phase stout class wood pole overhead distribution line, having a pole height of 9m and an average span length of 90m. For the structure, a 2.5m steel crossarm, a 0.75m crossarm strut and an 80mm insulator bracket (only for the central phase insulator) are used. The pole structure and conductor geometries are shown in Fig. 1.

The line is strung with ACSR Dingo conductors of 150mm^2 nominal area. A mid-span sag of 1.55m was assumed for a 50^{0}C conductor temperature which is sufficient to produce a minimum clearance of 5.8m above ground.

A single 33kV porcelain pin insulator with 185kV critical flashover voltage (CFO) was used. The line was assumed to be located on flat terrain with ground flash density of 1 flash/km^2/year.

For lightning protection of the line, gapless metal oxide surge arresters with a nominal discharge current of 10kA, a Maximum Continuous Operating Voltage (MCOV) of 32 kV and an energy capability of 3.6kJ/kV were used. Table 1 shows the volt-current characteristic of the arrester used.

The pole was modelled without top branches where it is represented by a simple propagation element which has a surge impedance equal to the pole surge impedance, a propagation length equal to the pole height and a propagation speed equal to the velocity of light (300 m/μs).

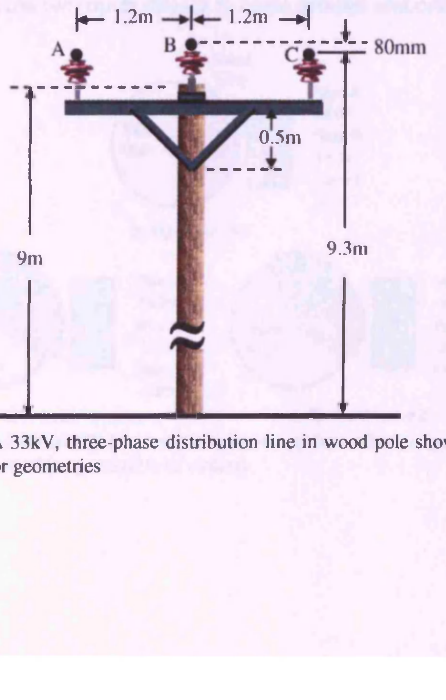


Fig. 1. A 33kV, three-phase distribution line in wood pole showing conductor geometries

Table 1 : Surge arrester volt-current characteristic

I (kA)	1	2.5	5	10	20
V (kV)	93.0	98.6	104.2	112.0	127.2

A non-linear footing resistance model was used, keeping the ratio between soil resistivity and the pole low-frequency resistance equal to 10 in all cases. A total line length of 10 spans was used. In the simulation, coupling matrices were connected at the two line ends to avoid reflections. Each simulated span section was further divided into 20 small sections to enable strokes at a number of points along the span. For all cases, 2000 transient simulations were performed statistically with random lightning strikes having magnitudes between 1.2 and 161.1kA and rise times in the range between 1.2 and 4.38μs. A fixed time to half-value of 75μs was assumed. In each statistical simulation, electrogeometric modelling was carried out on 3 spans.

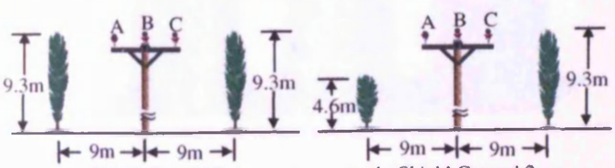
LIGHTNING PROTECTION STUDY

Overhead distribution lines are likely to have different kinds of nearby objects along their right of way. These objects may provide natural shielding to the overhead line and to some extent help protect the line from lightning. In order to recommend appropriate arrester configuration in each case, an open ground and two cases of naturally shielded ground were studied separately. Fig. 2 illustrates two typical cases of naturally shielded ground considered in this study.

It was observed that the surge arrester earth terminal connection plays a major role in determining the protection level of the line. Two cases were closely examined. Case 1: Unearthed Crossarm (Isolated surge arrester earthing) and Case 2: Earthed Crossarm (Non-isolated surge arrester earthing).

In Case 1, the surge arrester earthing terminal was considered to be earthed with an insulated earthing cable isolated from the wood pole and metal crossarm structure. In Case 2, it was considered to be connected to the steel crossarm strut earthed with a bare conductor passing along the surface of the wood pole structure. To simulate these two cases, two parameters were varied.

The surge impedance of the wood pole in a distribution line is very large, and when a bare earth conductor is placed along its surface (Case 2), the value considerably reduces. Using values calculated in the literature [6], pole surge impedances of 4645Ω and 224Ω were adopted in Case 1 and Case 2 respectively. The other important parameter that varies in each case is the CFO of the flashover path. In Case 1, the wood pole has high surge impedance with an unearthed crossarm, and flashover can take place only



a. Shield Ground 1 b. Shield Ground 2

Fig. 2. Two cases of naturally shielded ground

between phases. The weakest flashover path is between phase conductors through the crossarm. The total CFO of this path was calculated using the extended CFO-added method recommended by the IEEE Std. 1410-2004 [1] as follows.

$$CFO_{Total} = CFO_{ins} + 0.45CFO_{ins} \quad (1)$$
$$= [185 + (0.45 \times 185)]\ kV = 268.25kV$$

CFO_{ins} is the CFO of a 33kV pin insulator.

In Case 2, since the crossarm is earthed, the flashover path is simply between the phase conductor and the earthed crossarm. Therefore, the pin insulator alone provides the total CFO for the flashover path (185kV).

Electrogeometric modelling (EGM)

EGM studies were performed to identify the stroke distribution along the line so that appropriate arrester configuration and spacing could be selected. To represent stroke distribution in flat ground, a modified two-line CIGRE stroke distribution [7] was chosen with downward leaders approaching the line vertically. The striking distance to line conductor (R_c) and earth (R_e), in this case, was computed as [8]

$$R_c = 10\, I^{0.65} \quad (2)$$

$$R_e = [3.6 + 1.7\ln(43-h)]\, I^{0.65} \text{ for } h < 40\text{ m} \quad (3)$$

where I is the lightning impulse current magnitude and h is the average conductor height.

Fig. 3 shows a summary of EGM carried out with 20,000 stroke samples on the simulated line for open ground and two types of shielded ground. It clearly shows that the two outer phase conductors receive more than 85% of strikes hitting line conductors in open ground. However, in the naturally shielded ground, where height of the shielding object is at least equal to the height of the conductor, more than 88% of the strikes hitting the line conductors are collected by only one outer phase (phase A in this case).

This study presents critical information for selection of surge arrester configuration on the line. It is important to note that the two outer phases in open ground and one outer

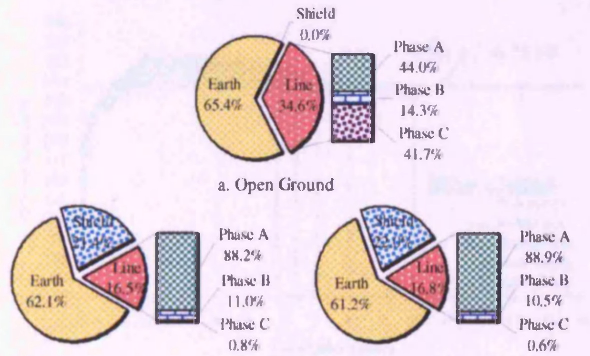


Fig. 3. Results of EGM for an open ground and two different cases of naturally shielded ground (% of strikes)

phase in naturally shielded ground must be considered in order to gain substantial lightning protection of the line.

Surge arrester protection

In distribution lines, surge arresters can protect lines against both direct lightning strikes and lightning induced voltages. The induced voltage flashover rate depends upon the CFO of the flashover path. In unprotected lines, the induced voltage flashover rate is negligible compared with the direct strike flashover rate for CFO of nearly 200kV or more [2]. The effect of the induced flashover can also be neglected when the surge arresters are separated by less than three spans along the line [1]. In this study, both conditions were satisfied and, therefore, the effect of induced overvoltage is ignored.

Fig. 4 shows the flashover performance of the line without surge arresters. It is obvious that the natural shielding helps to protect the line. We can see that the natural shielding considered in this case can provide more than 50% protection to the line. It can also be observed that for the line without surge arresters, an earthed crossarm does not make any significant difference to its lightning performance. However, this is not true when surge arresters are used to protect the line, as described in the following sections.

Open ground

Table 2 presents the lightning performance of the line in open ground for four different arrester configurations selected based on the EGM study. It can be seen that arresters connected to an unearthed crossarm (isolated surge arrester earthing) cannot provide significant protection unless if they are installed on each phase and at every pole. The EGM study shows that, in open ground, more than 85% of the direct strikes on phase conductors hit the two outer phases only. This means that installing arresters on the two outer phases should provide at least 85% protection to the line but, in this case, only about 28% protection to the line is achieved. On the other hand, with the earthed crossarm (non-isolated surge arrester earthing), the condition is different, and installing arresters on the two outer phases only can provide more than 85% protection to the line.

When the crossarm is not earthed, the flashover path could not be protected by arresters placed on only one phase. Even when lightning strikes the phase where a surge arrester

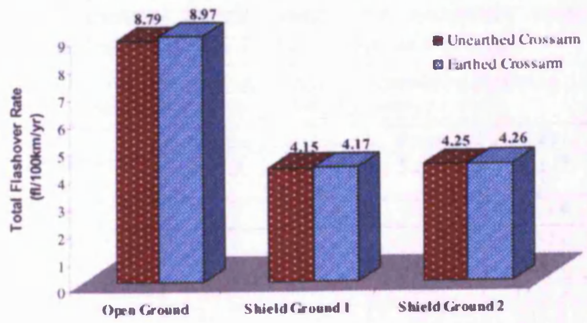


Fig. 4. Flashover performance of the line without surge arrester in different ground conditions

Table 2 : Lightning performance of the line in open ground for different arrester configurations

Arrester Configurations →	Total Flashover Rate (flashes/100km/year)				
Unearthed Crossarm	8.79	0.03	6.33	5.79	7.65
Earthed Crossarm	8.97	0.00	1.29	4.67	4.94

• mark indicates surge arrester on the phase at every pole

♦ mark indicates surge arrester on the phase at every alternate pole

is installed, flashover occurs between that phase and the phase without arrester. It is also important to observe that arresters installed on each phase and at every pole could not provide full protection to the line against lightning. Few flashovers were recorded when high-current lightning hits the phase conductor. Here, the overvoltage magnitude produced between phases due to high-current lightning strikes was more than the CFO of the defined flashover path resulting into flashover between the phases. Fig. 5 shows a typical overvoltage shape exceeding CFO when a high-current impulse strikes phase conductor *A* at different points along a span.

With the earthed crossarm, the surge arresters are in parallel with the flashover path and, hence, give better protection than the case with unearthed crossarm. A 100% protection could be achieved with arresters on all phases and poles. Installing arresters at alternate poles is not necessary for all cases, since it does not provide better protection to the line.

Naturally shielded ground

Table 3 shows lightning performance of the line for two different cases of naturally shielded ground in the cases of four different arrester configurations selected based on the EGM study. This case also agrees with the previous findings. In both cases, installing the arrester on one phase only at all poles with earthed crossarm can provide 85% protection to the line. Installing arresters on phases *A* and *B* at all poles can give more than 96% protection against lightning. Even though an earthed crossarm does not make any difference to the line lightning performance when not protected, it is shown that it is advantageous to earth the crossarm and connect the arrester earth terminal to it to obtain better lightning protection.

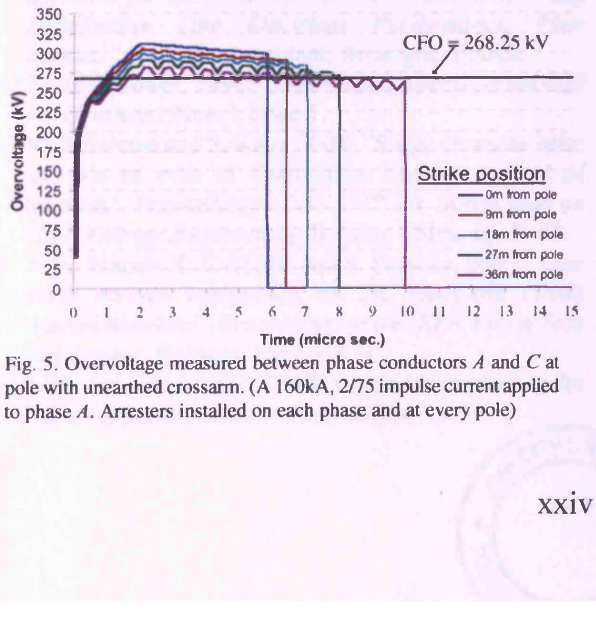


Fig. 5. Overvoltage measured between phase conductors *A* and *C* at pole with unearthed crossarm. (A 160kA, 2/75 impulse current applied to phase *A*. Arresters installed on each phase and at every pole)

Table 3 : Lightning performance of the line in two cases of naturally shielded ground for different arrester configurations

Arrester Configurations →		Total Flashover Rate (flashes/100km/year)				
Shield Ground 1	Unearthed Crossarm	4.15	0.02	3.50	3.59	3.84
	Earthed Crossarm	4.17	0.00	0.16	0.54	0.64
Shield Ground 2	Unearthed Crossarm	4.25	0.02	3.45	3.55	3.94
	Earthed Crossarm	4.26	0.00	0.15	0.58	0.69

• mark indicates surge arrester on the phase at every pole

♦ mark indicates surge arrester on the phase at every alternate pole

SURGE ARRESTER ENERGY DUTIES

Surge arrester energy duties were computed statistically with 2000 simulations for selected arrester configurations that provided better protection for the line. Only high energy values are presented in terms of cumulative frequency distributions. When two or more arresters are installed, they are not equally stressed. Table 4 shows the energy associated with the highly stressed arrester in open ground, and Table 5 shows this energy in the case of naturally shielded ground. In both cases, with earthed crossarm, arresters installed on all three phases are stressed with around 300kJ of energy with a probability of 0.05%. Since the line receives around 9 strokes/100km/year in open ground and 4.1 strokes/100km/year in shielded ground, the probability of this situation to occur per 100km is only once in 222 years in open ground and 487 years in naturally shielded ground. The tables clearly show that the arresters are not highly stressed even if the line is protected in open ground with two arresters on the outer phases and in naturally shielded ground with only one arrester. As can be seen, in both cases, the probability of arrester energy exceeding its maximum energy capability (115.2kJ) is less than 2%.

It can be seen that in case of unearthed crossarm, arresters on all three phases can only give 2% energy duty that is below the energy capability of the arrester used in this study. For other arrester configurations (two or one arresters only), the energy duty is 10%, which indicates high probability of arrester failure on the line. Compared with the case of arresters on all phases, the maximum energy absorbed by the arrester is also exceptionally high.

Table 4 : Arrester energy (kJ) in terms of cumulative frequency distribution for open ground (High energy values)

Probability (%)	Earthed Crossarm		Unearthed Crossarm	
0.05	299.2	429.6	284.2	9615.9
0.5	178.1	180.4	153.0	3150.2
1	130.5	134.1	127.6	2003.7
2	98.2	103.1	96.0	1231.2
5	65.6	66.0	65.7	317.8
10	47.1	48.2	47.0	98.1
20	31.1	29.7	30.2	38.1

Table 5 : Arrester energy (kJ) in terms of cumulative frequency distribution for naturally shielded ground 1 (High energy values)

Prob. (%)	Earthed Crossarm			Unearthed Crossarm		
0.05	298.5	516.5	575.2	316.2	7419.9	13133.7
0.5	192.0	183.7	244.0	186.1	1303.7	3056.8
1	163.2	145.9	204.5	152.2	711.8	1448.3
2	121.6	112.6	123.7	115.1	341.2	795.6
5	54.4	87.7	90.0	89.7	197.2	231.9
10	8.5	63.0	69.1	20.9	70.14	89.4
20	0.0	0.0	42.9	0.28	37.07	43.3

CONCLUSION

Surge arrester protection of a 33kV wood pole distribution line was investigated. It was shown that adequate selection of surge arrester configuration can protect the line effectively against lightning. Arresters connected to earthed crossarms allow better protection of the line compared with the case of unearthed crossarms. Arrester failure probability is low in the earthed crossarms case. Adequate overvoltage line protection can be provided with surge arresters installed on the two outer phases in the case of a line in open ground or with a single surge arrester in the case of a line in naturally shielded ground.

Acknowledgment

The authors wish to thank Engineering and Physical Sciences Research Council (EPSRC) for financial support.

REFERENCES

[1] IEEE Std. 1410-2004, "IEEE Guide for improving the lightning performance of electric power overhead distribution lines".

[2] T. E. McDermott, T. A. Short and J. G. Anderson, 1994, "Lightning protection of distribution lines", *IEEE Trans. on Power Delivery*, vol. 9, 138-152.

[3] J. McDaniel, 2006, "Lightning protection of distribution lines: Things to consider for a reliable design", *2005/2006 IEEE PES Transmission and Distribution Conference and Exhibition*, Dallas, USA, 1229-1232.

[4] Sadovic Consultant, 2005, "*SIGMA Slp-Version 2.1, Software for the Determination of Transmission and Distribution Line Electrical Performance, User Manual*", Sadovic consultant, Boulogne, France.

[5] Scottish Power, 1996, "*Distribution Specification-L20 for Overhead Lines*", Issue 1.

[6] M. Solaiman and S. Kato, 2005, "Surge characteristics analysis of pole in distribution line by method of moment", *Proceedings of the XIVth Int. Symposium on High Voltage Engineering*, Beijing, China, pp. B-40.

[7] Y. A. Wahab, Z. Z. Abidin and S. Sadovic, 2003, "Line surge arrester application on the quadruple circuit transmission line", *Proceedings of the IEEE PowerTech Conference*, Bologna, Italy, vol. 3.

[8] IEEE Std. 1243-1997, "IEEE Guide for improving the lightning performance of transmission lines".