Chapter 2

Insulation co-ordination for AC transmission and distribution systems

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2.1 Introduction

The international standard covering insulation coordination is IEC publication 60071. According to the IEC, insulation co-ordination comprises the selection of the electric strength of equipment and its application, in relation to the voltages which can appear on the system for which the equipment is intended and taking into account the characteristics of available protective devices, so as to reduce to an economically and operationally acceptable level the probability that the resulting voltage stresses imposed on the equipment will cause damage to equipment insulation or effect continuity of service.

The operation of a transmission system will present the system insulation with various types of voltage stress from the continuous voltage at which it must operate to various forms of overvoltage.

Overvoltages can be classified into two groups. The first group is externally generated overvoltages from lightning which manifests itself in two ways: by direct strikes to the lines or substations and by strikes to the towers or overhead earth wires from which back flashover voltages from the towers to the conductors can occur. The second group comprises internally generated overvoltages due to switching. These include the switching of capacitive and electromagnetic loads and travelling waves due to the energising of transmission lines. Also taken into consideration are power frequency overvoltages which are caused either by load rejection or by voltage changes on the two healthy phases when a single phase fault occurs.

Up to about 300 kV experience indicates that the highest voltage stress arises from lightning. For transmission systems above 300 kV the switching overvoltages increase in-importance so that at about 550 kV the point has been reached where they are equivalent to that of lightning overvoltages.

Power frequency voltages are important since they affect the rating of protective arresters or co-ordinating gaps which provide a means of controlling the overvoltages for the purpose of insulation co-ordination.

The complexity of insulation co-ordination may be visualised from the flow diagram shown in Figure 2.1, which indicates some of the factors involved and their interrelationship. The procedure takes an iterative approach where several scenarios for insulation co-ordination may be under consideration. Evaluation of the dielectric stresses imposed on the insulation may be carried out using a range of computer models determined from the system characteristics to enable the selection of the insulation requirement. To assist with the selection of insulation levels IEC 60071 has 'Standard Insulation Levels', an extract from which is shown in Figure 2.2 and Table 2.1 for system voltages in the range 300 kV to 550 kV.

2.2 Classification of dielectric stress

The following classes of dielectric stresses (see Figure 2.3) may be encountered during the operation of the transmission system:

1. power frequency voltage under normal operating conditions
2. temporary overvoltages
3. switching overvoltages
4. lightning overvoltages.

2.2.1 Power frequency voltage

Under normal operating conditions the power frequency voltage can be expected to vary somewhat but, for the purpose of insulation co-ordination, is considered to be constant and equal to the highest system voltage for the equipment.

2.2.2 Temporary overvoltages

The severity of temporary overvoltages is characterised by amplitude and duration. This overvoltage is a significant factor when considering the application of surge arresters as a means of surge voltage control. Although the surge arrester is not used for the control of temporary overvoltages it results in a considerable increase in the resistive component of leakage current in a metal oxide gapless surge arrester. This results in a temperature rise within the surge arrester and the possibility, if left long enough, of arrester failure.

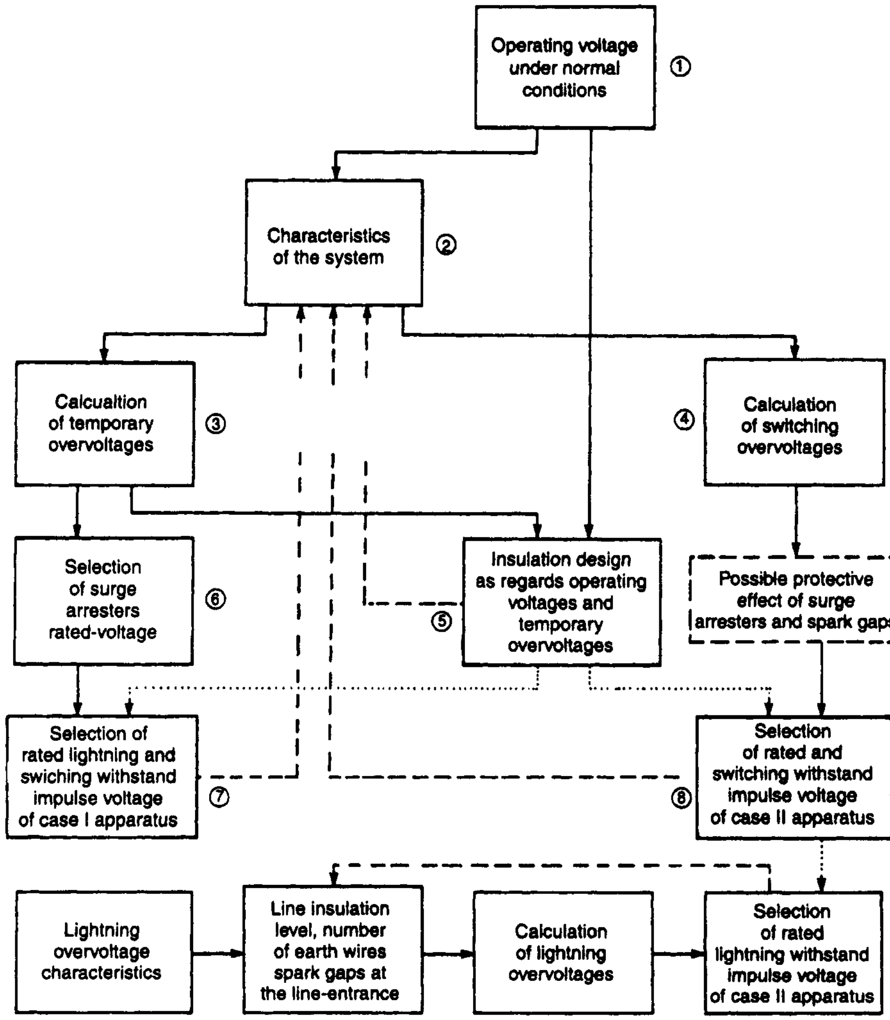


Figure 2.1 Block diagram of insulation co-ordination and design

Temporary overvoltages arise from (i) earth faults, (ii) load rejection and (iii) resonance and ferroresonance.

When considering earth faults, the voltage on the healthy phases will rise during the fault period to values approaching line voltage dependent on neutral earthing arrangements. Typically for 420 kV systems a value of 1.5 times normal system phase voltage can result for periods up to 1 s, by which time the fault is usually cleared.

Load rejection can, on long uncompensated transmission lines, produce voltages of 1.2 times nominal system voltage, due to the *Ferranti*

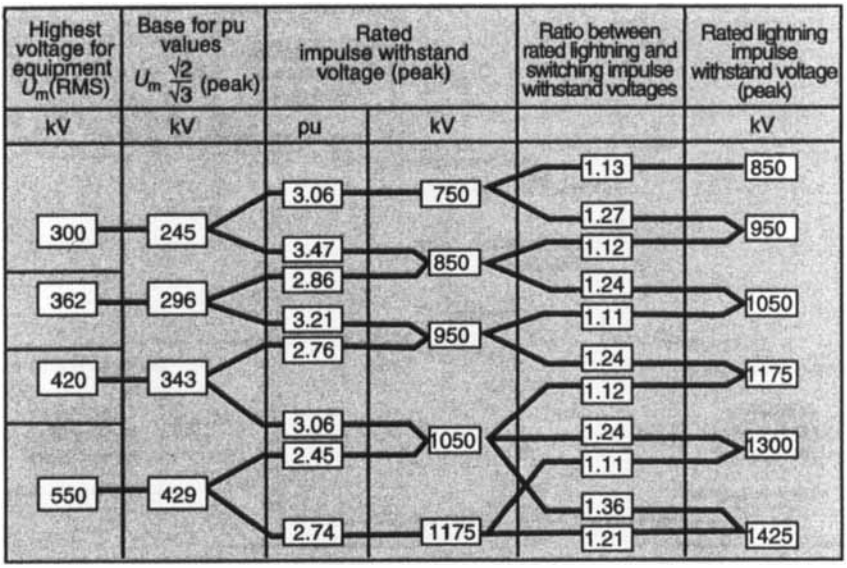


Figure 2.2 Standard insulation levels

effect, at the substation end of the line which is disconnected from the source (i.e. remote end). The Ferranti effect is caused by the current flow through the line shunt capacitance which produces a voltage across the source and line inductance which increases with distance from the source end of the line.

Temporary overvoltages due to resonance and ferroresonance conditions generally arise when circuits with large capacitive elements (transmission lines, cables, etc) and inductive elements (transformers and shunt reactors) having nonlinear magnetising characteristics are energised, or through sudden load changes. Parallel line resonance can also occur during de-energisation of one circuit of a double circuit transmission line which has shunt reactive compensation. The energised line feeds the resonance condition through the intercircuit capacitance and voltages as high as 1.5 times nominal system phase voltage have been recorded on 420 kV systems [1]. This voltage will remain at this level until the line is energised or until the compensating reactor is switched out. Magnetic voltage transformers can also produce ferroresonance conditions but usually these are sub-third-harmonic and the resultant voltage is close to nominal system voltage [2]. This resonant voltage will not present any problem for the insulation but the VT primary current will be many times the nominal current and the resultant heat generated in the primary winding would be of prime concern for the VT insulation. However, fundamental ferroresonance can also occur with VTs and voltages in excess of two times nominal system voltage have been reported. If ferroresonant conditions are indicated during a system study then design

Table 2.1 Standard insulation levels from IEC 60071

Highest voltage for equipment U_m	Standard switching impulse withstand voltage			Standard lightning impulse withstand voltage
	Longitudinal insulation (+)	Phase-to-earth	Phase-to-phase (ratio to the phase-to-earth peak value)	
kV (RMS value)	kV (peak value)	kV (peak value)		kV (peak value)
300	750	750	1.50	850 950
	750	850	1.50	950 1050
362	850	850	1.50	950 1050
	850	950	1.50	1050 1175
420	850	850	1.60	1050 1175
	950	950	1.50	1175 1300
	950	1050	1.50	1300 1425
550	950	950	1.70	1175 1300
	950	1050	1.60	1300 1425
	950	1175	1.50	1425 1550

modifications may be considered or steps can be taken to avoid the switching operations that cause them or to minimise the duration by selection of an appropriate protection scheme.

2.2.3 Switching overvoltages

Switching overvoltages according to IEC 60071 can be simulated by a periodic waveform with a front duration of hundreds of microseconds and a tail duration of thousands of microseconds. The waveform shown in Figure 2.3 may be typical of switching surges which have in practice a decaying oscillatory component superimposed on the power frequency waveform. Of major importance are the switching surges produced by line energisation and re-energisation which cause travelling waves on

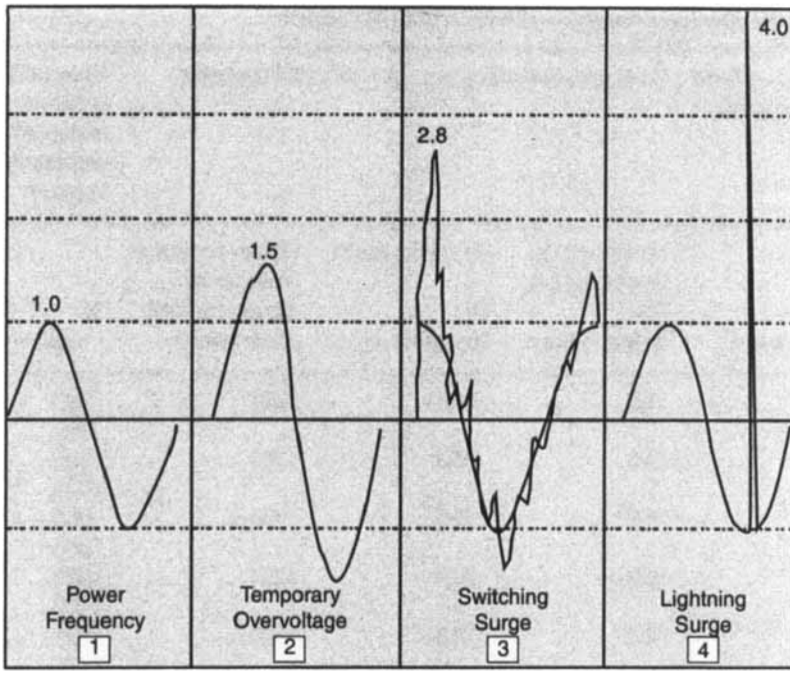


Figure 2.3 Classification of dielectric stress

the transmission line and are most severe at the end remote from the switching point. This will be discussed later in more detail.

2.2.4 Lightning overvoltages

Lightning overvoltages according to IEC 60071 can be simulated by an aperiodic wave with a front duration of the order of 1 μs and a tail duration of the order of several tens of microseconds. The lightning surge voltage is produced by a strike to the tower or earth wire which either induces a voltage in the phase conductors or by back flashover of the line co-ordinating gap injects current into the phase conductor. A direct strike to the phase wire can also occur if the phase wire is not well shielded by the earthwire. The voltage wave front arriving at the substation can be significantly affected by the line termination, and with cable terminations the wave front may be drastically reduced to the extent that it more resembles a fast switching surge. This will be discussed later in the chapter.

2.3 Voltage-time characteristics

In practice the waveform of lightning overvoltages varies considerably, but for the purpose of testing equipment there is an internationally agreed wave shape used which has a rise time of 1.2 μs and a time of decay of 50 μs to 50% of the maximum amplitude.

Switching overvoltages vary from oscillatory voltages of several tens of thousands of cycles per second to travelling waves with a rise time of up to 1000 μs. It is now generally accepted that the withstand strength of air insulation is a minimum for a wave with a rise time of approximately 250 μs and with a decay time to 50% of 2500 μs, although there is a tendency for this minimum to occur at longer wave fronts as the airgap increases. Similarly, the minimum under oil withstand strength occurs with a wave front of approximately 100 μs.

Gas insulated substations (GIS) have a virtually flat voltage-time (*V-t*) characteristic from power frequency through to the switching surge range and show an upturn near the 10 μs point.

Figure 2.4 shows a typical *V-t* characteristic for 420 kV GIS along with a range of dielectric stresses. From the standard insulation levels (IEC 60071) 420 kV equipment can have a 1425 kV lightning impulse withstand level (LIWL) with a corresponding 1050 kV switching surge level (SIWL) based on a rated voltage of 420 kV (RMS), i.e. a phase voltage peak of 343 kV.

The voltage-time characteristic of insulation used in equipment must be carefully assessed when comparing performance with lightning and switching surges. Also the *V-t* characteristics of protective devices must be considered; for example, co-ordinating gaps in air will not offer practical protection of GIS against switching or lightning surges because the *V-t* characteristics are totally incompatible.

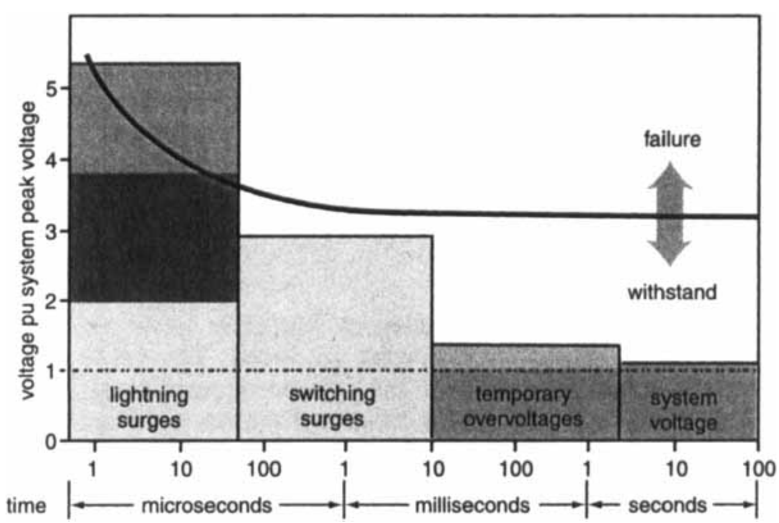


Figure 2.4 Voltage-time characteristics

2.4 Factors affecting switching overvoltages

When energising or re-energising transmission lines severe overvoltage can be generated [3]. The overvoltage magnitude is dependent on many factors including the transmission line length, the transmission line impedances, the degree and location of compensation, the circuit-breaker characteristics, the feeding source configuration and the existence of remanent charge from prior energisation of the transmission line.

The magnitude of these switching transients is the main factor determining the insulation levels for EHV and UHV transmission systems; consequently reduction in their severity has obvious economic advantages. The two methods used to achieve substantial reduction in transmission line energising overvoltages are resistor insertion [4] and controlled closing of the energising circuit-breaker close to voltage zeros [5]. There have, however, been instances where both methods have been combined for overvoltage reduction in a UHV system [6]. Alternatively, for systems up to 550 kV, gapless metal oxide surge arrestors can also be used to reduce the phase-to-earth switching surge overvoltages to below 2.4 pu of system nominal phase voltage peak.

2.4.1 Source configuration

Source networks can very crudely be split into two types: (a) those with purely inductive sources, i.e. where no lines are connected to the energising busbar, e.g. a remote hydro station; and (b) those with complex sources, i.e. with lines feeding the energising busbar or a mixture of lines and local generation.

Much work has been done over the years on both types of sources [7–9]. Trends are more easily defined with the simple lumped source, and normally slight increases in overvoltages are obtained with increase in source fault level except where resonance conditions are approached with very low source fault levels. With the complex source configuration no general trends exist due to a large number of interacting parameters in the source network.

2.4.2 Remanent charge

The remanent charge on a transmission line prior to its reclosing has a significant effect on the overvoltages produced. The value of trapped charge is very much dependent on the equipment permanently connected to the line, as this determines the decay mechanism (see Figure 2.5).

If no wound VTs, power transformers or reactors are connected, the line holds its trapped charge, the only losses being due to corona and leakage and thus the decay is very much weather dependent. In good weather conditions the time constant of the decay is of the order of

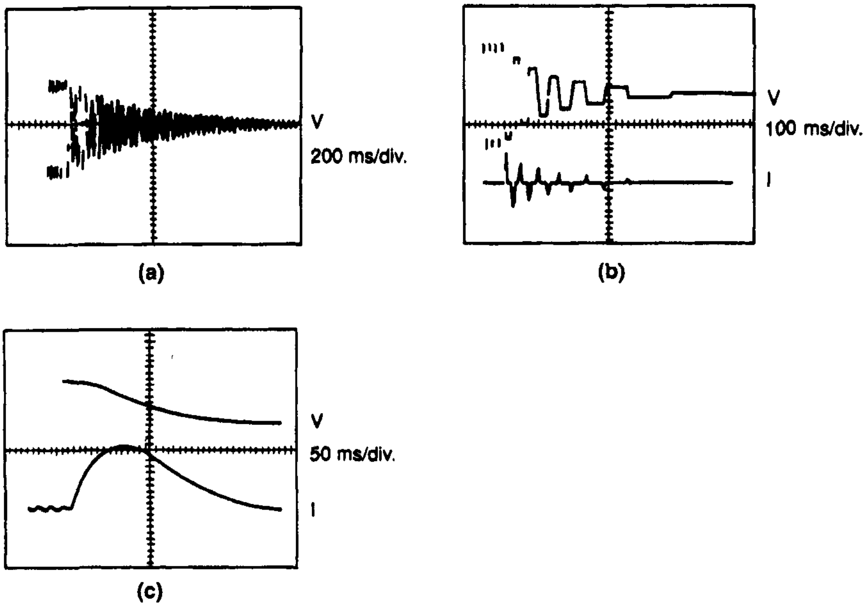


Figure 2.5 *Decay of trapped charge by:* **(a)** *reactor;* **(b)** *power transformer;* **(c)** *voltage transformer*

10–100 s so that no appreciable discharge will occur in an automatic reclosure sequence.

With a power transformer connected to the transmission line the trapped electromagnetic energy oscillates within the RLC circuit formed by the line and transformer. The transformer oscillates between the saturated and unsaturated state resulting in a decay in some 5–50 cycles of the supply frequency. Figure 2.6 shows a computer simulation of the three-phase decay of trapped charge with initial overvoltage when the circuit-breaker opens due to mutual coupling effects.

The decay mechanism with a wound magnetic voltage transformer is similar to the power transformer but the damping is much more effective due to the high winding resistance, of the order of several tens of k-ohms, of the voltage transformer. Most of the stored energy on the line will be dissipated in the first hysteresis loop of the voltage transformer core mainly due to copper loss, although conditions have been encountered with long transmission lines and wound VTs in SF_6 insulated substations where complete dissipation requires 5 cycles of the supply frequency.

When a shunt reactor is connected to the line, on de-energisation an oscillation exists determined by the line capacitance and the reactor similar to the power transformer. In this case, however, there is no saturation and the oscillations are slowly damped due to high reactor Q-value. In

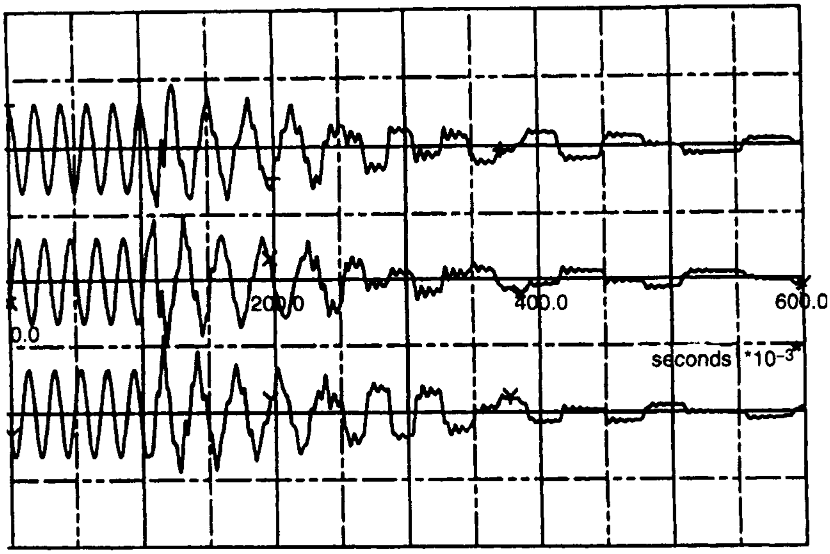


Figure 2.6 Decay of power transformer voltages (with saturation)

addition, beat effects are introduced due to mutual coupling effects. The damping time constant is of the order of seconds; thus only slight decay in the trapped charge occurs within a practical high speed auto-reclose time sequence.

2.4.3 Transmission line length

The length of transmission line being energised affects the overvoltage magnitude in that the longer the line the greater is the steady-state open-circuit receiving end voltage (Ferranti rise) on which the high frequency transients, the frequency of which is determined by the line length, are superimposed.

The frequency of the switching surge can be approximated by

$$f = 1/4T$$

where T is the transit time of the line ≈ {line length (in km)/0.3} μs assuming the surge travels along the line at the speed of light.

2.4.4 Compensation

Shunt reactor compensation has a two-fold effect when situated at the transmission line receiving end, both aspects of which contribute to a reduction in the severity of the energising overvoltages. The reactor reduces the magnitude of the Ferranti rise along the line by negating the effect of a portion of the line shunt capacitance and presents a line termination other than an open circuit to any travelling waves from the transmission line sending end. For a 420 kV line the capacitive line charging current is approximately 1 A per km (0.25 MVA per phase). A 200 km line would typically require 40 MVAr of shunt reactive compensation per phase depending on the system operational requirements.

2.4.5 Circuit-breaker pole scatter

Circuit-breakers will seldom produce a simultaneous close onto a three-phase transmission line for two reasons:

1. The circuit-breaker mechanism closes the contacts at high speed and mechanical tolerances will give a spread of closing times between the three phases. Typically this may be of the order of 3–5 ms between the first and last pole to close.
2. Depending on the point-on-wave at which the circuit-breaker initiates a close, the phase with the highest instantaneous value of power frequency voltage will pre-arc first, just before contact touch.

The pole scatter effect produces voltage through mutual coupling from the first phase to close on the other two phases. This pre-charging effect then produces a voltage greater than phase voltage across the contacts of the other two phases of the circuit-breaker. This in turn forces a greater than 1 pu step voltage to be applied as the other phases close. Certain critical points can be reached depending on the pole scatter time and point-on-wave (POW) of closure, for example when the second pole to close occurs at $2T$, $4T$ etc. for the transmission line, i.e. the point at which the switching surge on the first phase to close returns to the sending end of the line. By studying the various combinations of pole scatter, points of maximum/near minimum overvoltages can be determined. With Transient Network Analyser (TNA) studies, pole scatter diagrams can be created showing the effect of incremental changes in pole scatter and the maximum overvoltage position located. With computer analysis, using programs such as EMTP, a statistical approach is normally adopted using random point-on-wave (uniform distribution) with Gaussian distribution for pole scatter. From work previously carried out with TNA using 500 operations with random point-on-wave and circuit-breaker pole scatter determined from typical distribution curves, the 2% probability value (i.e. the overvoltage value which will be exceeded for 1 in 50 operations) was approximately 15% below the maximum value derived using the conventional (maximum) method.

2.4.6 Point-on-wave of circuit-breaker closure

The magnitude of the transient voltage is very much dependent on the instantaneous value of power frequency voltage at which the circuit-breaker closes. If all three poles of the circuit-breaker closed at voltage zeros then only a very small transient voltage would occur.

2.5 Methods of controlling switching surges

On systems of 400 kV and above, the energisation of long transmission lines (200 km and greater) is commonly required. Voltages above 4 pu of the normal system phase voltage peak have been shown to occur by TNA and computer studies. Methods therefore have been employed to reduce these overvoltages to 2.5 pu or less to achieve economic design of the transmission line and substation. At 420 kV the overvoltages can be well controlled using metal oxide surge arresters at the send and receive end of the line. At 550 kV, circuit-breaker pre-insertion resistors (PIR) have been used with great effect but result in complicated contact arrangements on the circuit-breaker with appropriate increase in maintenance. For 550 kV systems with line lengths below 300 km, metal oxide surge arresters (MOA) can give an acceptable voltage profile along the line length, with the maximum voltage occurring at the line mid-point. With lengths near 300 km and above, additional surge arresters can be placed at the line mid-points. Recent developments in controlled point-on-wave (POW) switching have introduced microprocessor based technology for circuit-breaker operation control. This can be very effective, particularly when used in conjunction with metal oxide surge arresters for transmission line overvoltage control. However, in all cases the substation voltages can be adequately controlled with the surge arresters at the line ends only. Dependent on the line design and the acceptable risk of failure for the 550 kV line, the mid-point surge arrester may not be required even with 300 km lines.

2.5.1 Circuit-breaker pre-insertion resistors

2.5.1.1 Single stage resistor insertion

Energising a transmission line through single stage resistors results in the waves transmitted along the line being reduced in magnitude and hence the overvoltages at the receiving end being less severe. Resistors used in this way must also be removed from circuit and the removal of the resistors also initiates travelling waves which create overvoltages. Figure 2.7 illustrates the severity of the overvoltages produced in the initial energising operations through single stage resistors and the subsequent resistor shorting operations indicating that there is an optimum PIR value where the overvoltages produced by the initial energisation and the subsequent resistor removal are equal.

The optimum resistor value varies with different system conditions but is typically in the range 300–500 ohms.

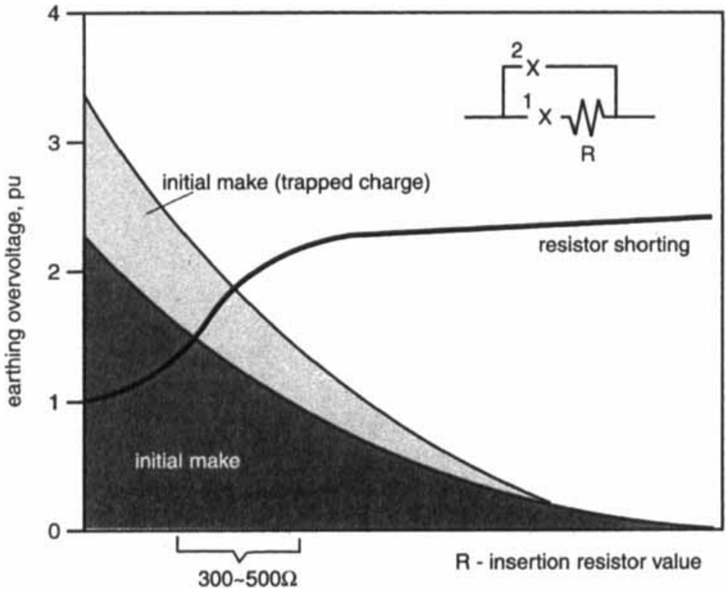


Figure 2.7 Overvoltage reduction with closing resistors

2.5.1.2 Insertion time and pole scatter

The overvoltages generated when energising transmission lines are relatively insensitive to the resistor insertion time. However, if the insertion time is less than the circuit-breaker pole scatter plus twice the transmission line transit time an increase in the overvoltage results, especially in the cases when remanent charge exists. Figure 2.8 illustrates the results from a series of studies to investigate the relationship between pole scatter and insertion time. They show that there is significant increase in the overvoltage if one phase is energised through its resistor and the resistor shorted out before another phase has been energised for the first time as the damping effect of the resistor on the mutually induced voltage is ineffective. The effect is most pronounced in the regions of small insertion resistor values where the mutually coupled transient components are greater.

2.5.2 Metal oxide surge arresters

2.5.2.1 Selection of surge arrester rating

The temporary overvoltage level and duration must be carefully considered before selecting the rating of the surge arrester (MOA). The surge arrester must be capable of withstanding, from thermal constraints, the temporary overvoltage (TOV) which in most circumstances determines the surge arrester rated value. From the rated value stems the

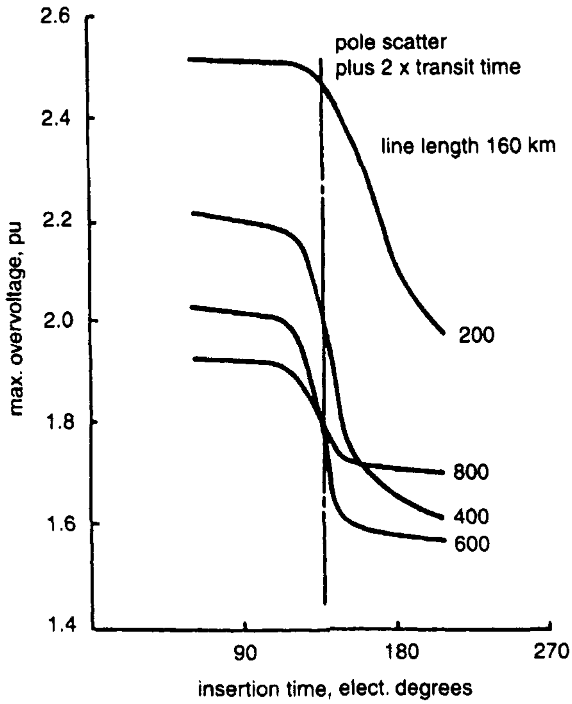


Figure 2.8 Overvoltage variation with resistor insertion time

protective or voltage limiting characteristic of the surge arrester – the higher the rating, the higher the limiting or residual voltage the arrester will have.

Thermal constraints are very important with MOAs since if the rating is too low, temporary overvoltage may cause excessive heating resulting in thermal instability with a runaway condition being produced and subsequent failure. Figure 2.9 shows typical TOV capability for MOAs. The energy capability of the surge arresters are usually expressed as kJ/kV of arrester rating. The maximum continuous operating voltage is considered as 80% of the rated voltage. Typically for 420 kV systems an arrester rating of 360 kV will be used which gives a maximum continuous operating voltage of 1.25 pu of nominal system voltage. From the curve given in Figure 2.9 a temporary overvoltage of 1.5 pu can be withstood for approximately 20 min with a 360 kV MOA. The surge arrester voltage-current characteristic exhibits an extremely nonlinear relationship once the 'knee' point voltage has been exceeded, which causes large increases in current for small voltage increase (see Figure 2.10). Typically for a 444 kV rated arrester (TOV capability of 1.7 pu for 10s on a 550 kV system) a residual voltage change from 860 kV to 1220 kV produces a

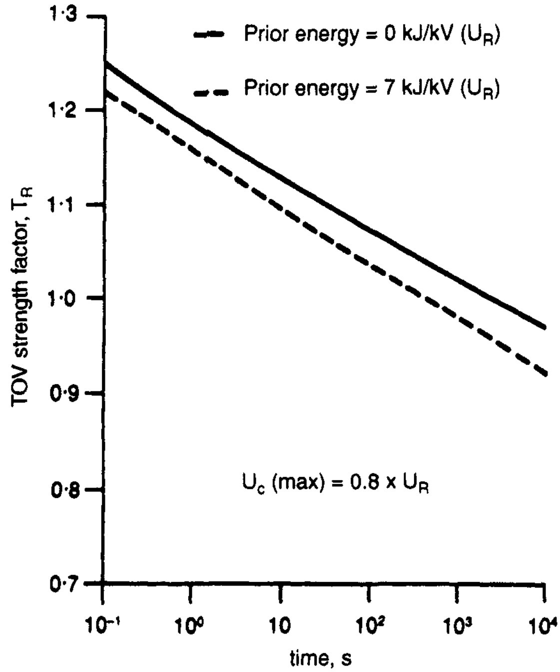


Figure 2.9 *TOV capability for typical surge arrester, expressed in multiples of $U_R(T_R)$*

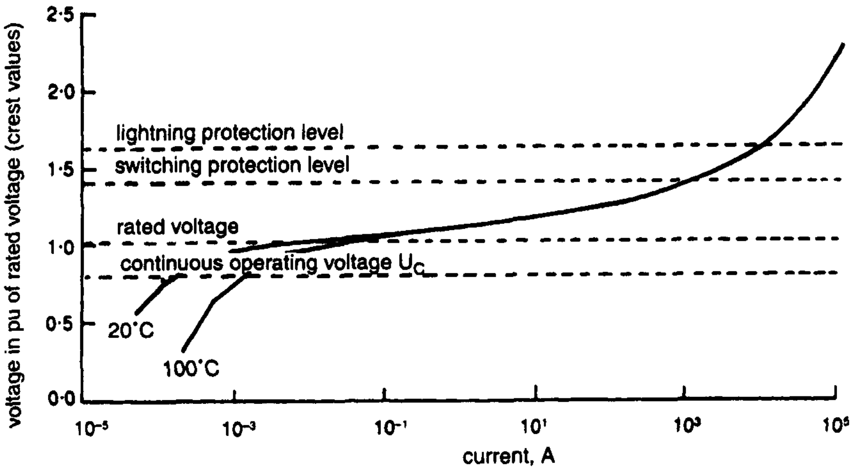


Figure 2.10 *Typical voltage-current characteristics for ZnO arresters*

current change from 1 kA to 40 kA. This arrester will also limit switching surges at the substation to approximately 2.4 pu on 550 kV systems. The rise time of the switching surge is relatively slow in comparison to the transit time of the substation busbars allowing surge arresters at the line end only to give complete substation protection.

2.5.2.2 Application of MOAs for switching surge reduction

For the 420 kV transmission system shown in Figure 2.11 the maximum switching surge is reduced from 2.15 pu to 2.03 pu (see Figure 2.12) by locating a 396 kV MOA at the line end. This is not surprisingly, a very small voltage reduction for a level of voltage which, even without MOA application, is well within the SIWL (3.0 pu) and would not justify the cost of surge arrester application. For this condition, the surge arrester draws a peak current of 190 A with a pulse width of 0.5 ms. Smaller current pulses are also evident for the other oscillations at the power frequency voltage peaks.

For the same transmission system Figure 2.13 shows the maximum overvoltage with trapped charge which is well in excess of the substation SIWL. For this condition a reduction from 4.28 pu to 2.35 pu in the switching overvoltage can be achieved with a 396 kV rated MOA. For

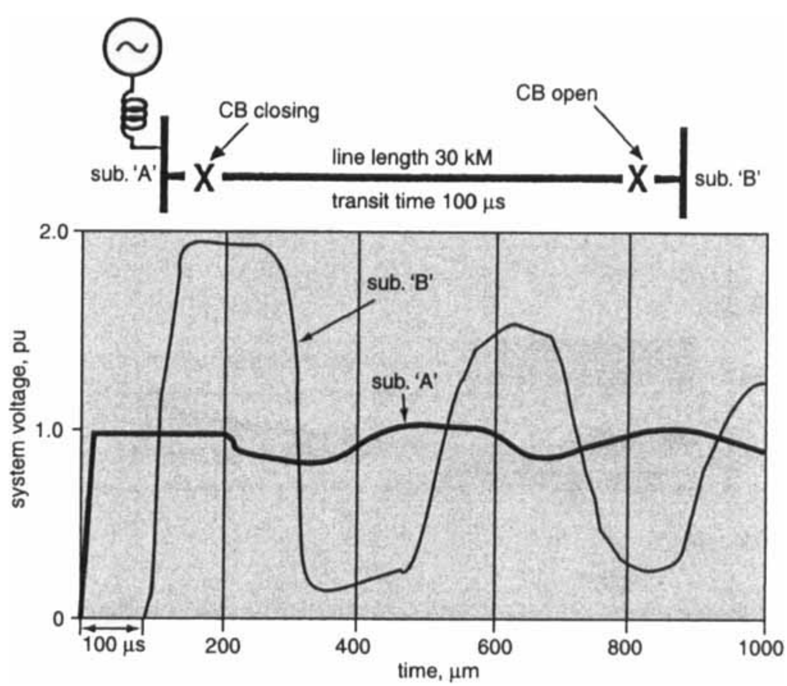


Figure 2.11 Switching surges – travelling waves

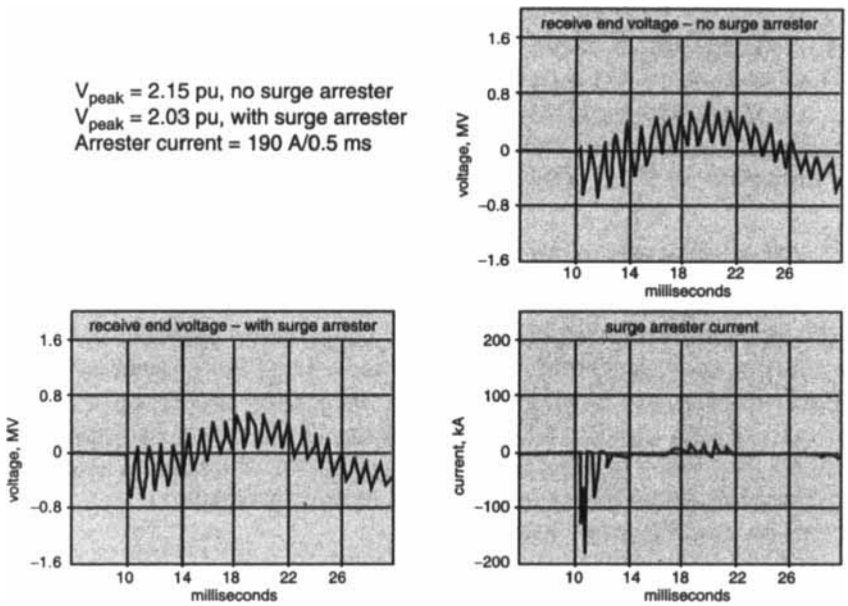


Figure 2.12 Control of switching surges using surge arresters (low level surge)

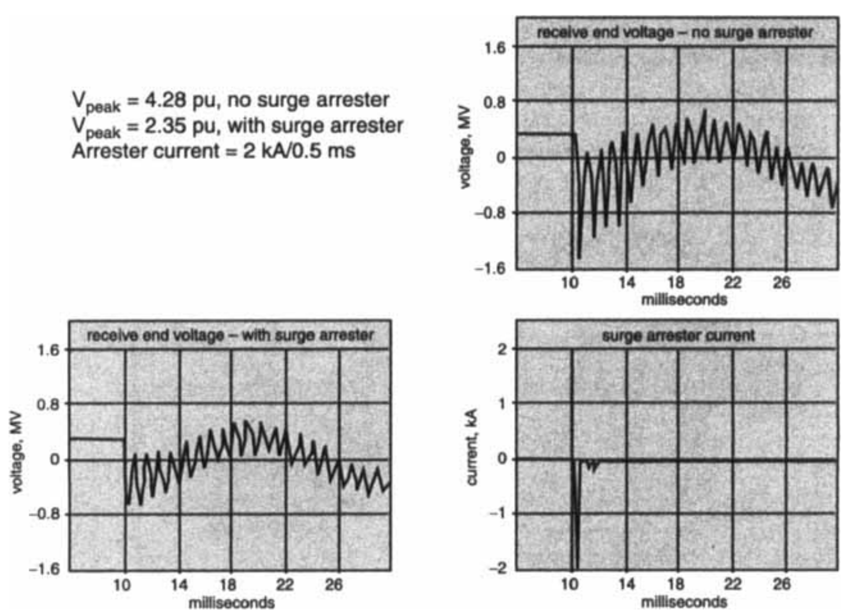


Figure 2.13 Control of switching surges using surge arresters (high level surge)

this case the surge arrester draws a 2 kA current pulse with a 0.5 ms width. By comparison of the two conditions, i.e. with and without surge arresters, not only is the amplitude significantly reduced but the oscillations are much more quickly damped. For the trapped charge (worst case) condition a safety factor (SIWL/protection level of MOA) of 1.27 has been achieved (IEC 60071 recommends a minimum of 1.15).

2.5.3 Circuit-breaker point-on-wave control

One method of switching overvoltage control which has been investigated over many years but recently has seen growing applications [10] is that of point-on-wave (POW) controlled switching. With modern circuit-breakers and the use of microprocessor technology, accurate point-on-wave control can now be achieved. The controller must be capable of compensative and adaptive control to allow for changes in operating conditions for the circuit-breaker as well as ageing effects.

It can be used for many applications:

- reactor switching
- capacitor bank switching
- transformer switching
- transmission line switching.

Each application has its own 'ideal switching' point and can be used for de-energising as well as energising conditions.

For the purpose of transmission line energisation (see Figure 2.14), the ideal closing point is the system power frequency voltage zeros – for re-energisation during auto-reclose operations the 'ideal' point will vary

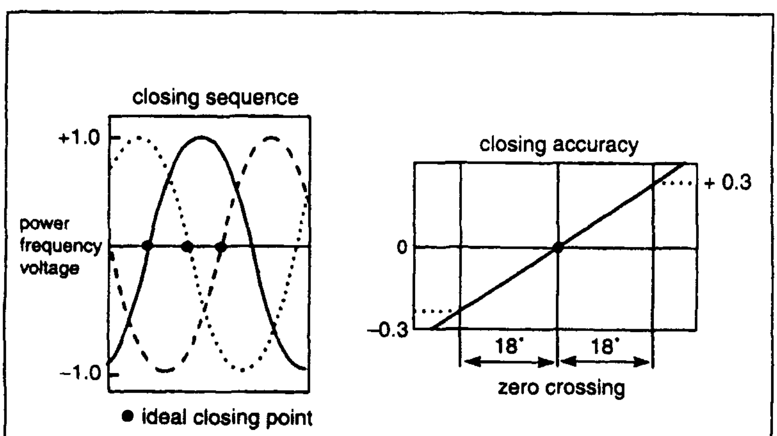


Figure 2.14 Point-on-wave switching control – transmission line energisation

depending on the line trapped charge conditions and is basically adjusted to a point at which there is zero voltage or minimum voltage across the contacts of the circuit-breaker.

Switching overvoltages can be reduced to levels below 2 pu providing the required timing accuracy of the circuit-breaker and controller can be achieved.

2.5.3.1 Circuit-breaker controller requirements

The controller must be capable of monitoring the control parameters of the circuit-breaker such as:

- DC auxiliary voltage
- stored mechanism energy
- temperature
- system frequency

and compensate for variations in these parameters.

Also, for adaptive purposes, the previous operating times, speeds and achieved accuracy must be recorded and taken into account when calculating the predicted operating time.

When controlling the closing point, account must be taken of pre-arcing between the circuit-breaker contacts. Pre-arcing effectively closes the circuit-breaker contacts before actual contact touch and can shortern the closing time by as much as 3 ms under certain conditions. The required timing accuracy of ± 1 ms means that a combined standard deviation for the circuit-breaker and controller of less then 0.4 ms must be achieved unless a higher risk of the switching overvoltages in exceeding 2 pu can be allowed.

If POW closing is used in conjunction with MOAs (as is the usual case since surge arresters are required for lightning surges) then the substation switching overvoltages will be well controlled and the major concern will then be the switching overvoltage profile on the transmission line.

2.5.4 Comparison of switching overvoltage control methods

When no control methods are used, the 2% probability voltage can exceed 4 pu at the receive substation, and overvoltages in excess of 3 pu can occur for 50% of the line energisations.

All three switching overvoltage control methods (PIR, MOA and POW) provide acceptable switching overvoltage control for the substation with the 2% probability voltage reduced to less then 2.0 pu.

However, when considering the line switching overvoltage performance, the line overvoltage profile has to be taken into account. In Figure 2.15 the curves have been plotted using the 2% probability voltages for each of the control methods and combinations. Various possibilities are shown here with the highest overvoltages occurring near the line

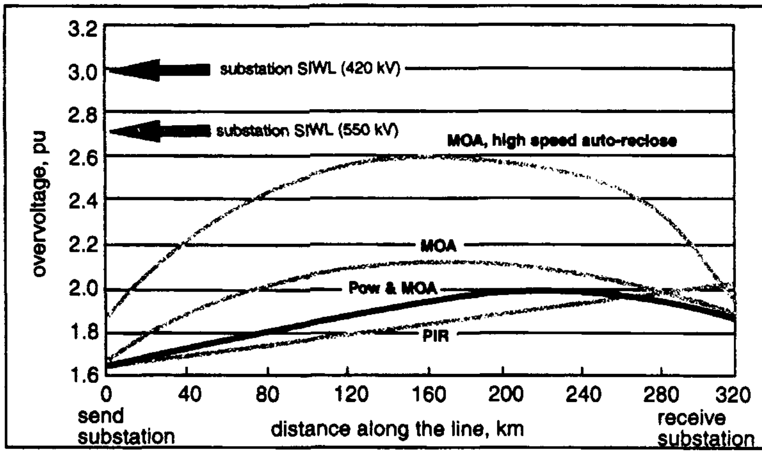


Figure 2.15 Comparison of control methods showing line switching overvoltage profile

mid-points for the MOA conditions. The PIR control shows the highest overvoltages at the receive end of the line.

Most line designs will be able to give a satisfactory performance with a 2% overvoltage less then 2.2 pu, for example, on 550 kV systems. This can be accommodated by all the control methods if high speed auto-reclose is not required. With high speed auto-reclose, the 'MOA only' condition produces an unacceptable profile with virtually 90% of the line exceeding the 2.2 pu overvoltage. Line mid-point surge arresters could be considered to improve the profile or additional methods of control would have to be used. For example, the use of magnetic voltage transformers at the line ends could be used in place of capacitive coupled VTs so that the line trapped charge will decay to a low value within the reclose period, alternatively, POW control or PIRs will have to be used.

When surge arresters are used with PIR and POW controls then the switching surge current taken by the arrester is much reduced, which can assist with its TOV handling capability – particularly for systems using multiple auto-reclose strategies. This may allow the application of lower rated surge arresters and therefore further enhance the overvoltage control.

2.6 Factors affecting lightning overvoltages entering substations

The magnitude and rate of rise of overvoltages due to lightning strikes on transmission lines is an important consideration for substation insulation and the strategy adopted for limiting these overvoltages.

Having determined the insulation required for the line, it is usual to find that the lightning withstand level is in excess of commercially available LIWL levels of the substation equipment. Thus, unless precautions are taken, overvoltages entering the station can cause undue insulation failure. Surge arresters can be situated at the line entrance but consideration must be given to the voltage profile as the surge travels through the substation. Alternatively, consideration may be given to using rod gaps, set to operate marginally below the station LIWL and SIWL levels, and fitted to the first three or four towers. However, consideration must be given to the voltage-time characteristic of the substation equipment in comparison to that of line gaps. For example, 132 kV and 420 kV GIS cannot be adequately protected by line co-ordinating gaps. Figure 2.16 shows a comparison of line gaps and a metal oxide surge arrester in relation to the standard insulation levels for a 420 kV GIS and shows that the 2 m line gap is totally ineffective as a method of reducing the incoming surge voltages.

The number of strikes to transmission lines is generally accepted to be related to the isoceraunic level which is defined as a number of days in a year in which thunder is heard at a given location. Assumptions are made in relating this isoceraunic level to the number of strikes to towers and earth wires; Reference 11 provides methods of calculating the number of line flashes - see Figure 2.17. The number of strikes is directly proportional to the isoceraunic level, i.e. a level of 20 entails twice the number of strikes as a level of 10.

The calculation method is based on the number of ground flashes that would occur to the area of ground shielded by the transmission line. Two possibilities exist for generating lightning overvoltages on the line conductors – the 'backflashover' and the 'direct' strike. Figure 2.18 shows a typical 420 kV single circuit tower illustrating the two strike conditions and gives the tower and line parameters.

2.6.1 Backflashover

A backflashover occurs as a result of the tower or shield wire being struck by lightning, the current passes to earth via the tower steelwork causing a voltage difference between the tower cross arms and the line conductors. The magnitude of this current can vary from a few kA to over 200 kA. The statistical data for amplitude and steepness of lightning currents is given in Figures 2.19 and 2.20 derived from data by Anderson and Eriksson [12].

Due to the height of the tower and rate of rise of current, a travelling wave can be set up on the tower. The combination of shield wire and tower surge impedance (see Figure 2.21) and lightning current impulse will produce a voltage at the tower top which is oscillatory due to successive reflections from the tower base. When the surge current arrives at the

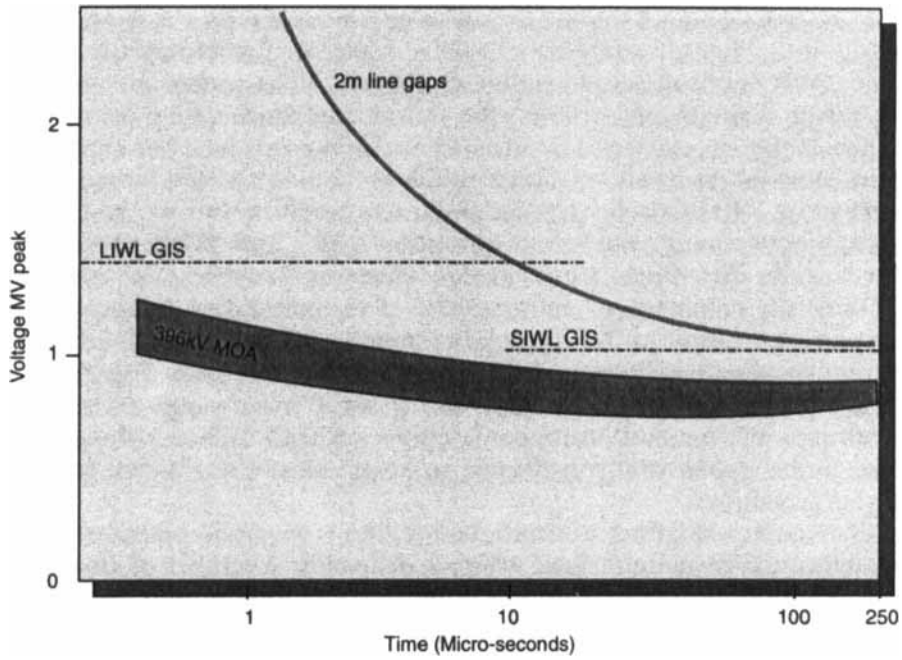
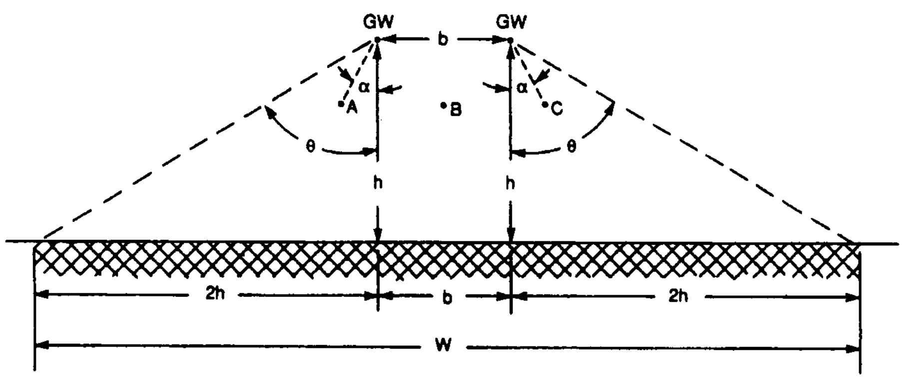


Figure 2.16 Comparison of voltage-time characteristics

Number of line flashes NL = $0{\cdot}012T\,(b + 4h^{1{\cdot}09})$



θ = shadow angle
α = shield angle between shield wire and phase conductor
W = shadow width or earths surface
GW = shield wire location
ABC = phase wires
T = isoceraunic level

Figure 2.17 Model for line flash calculations

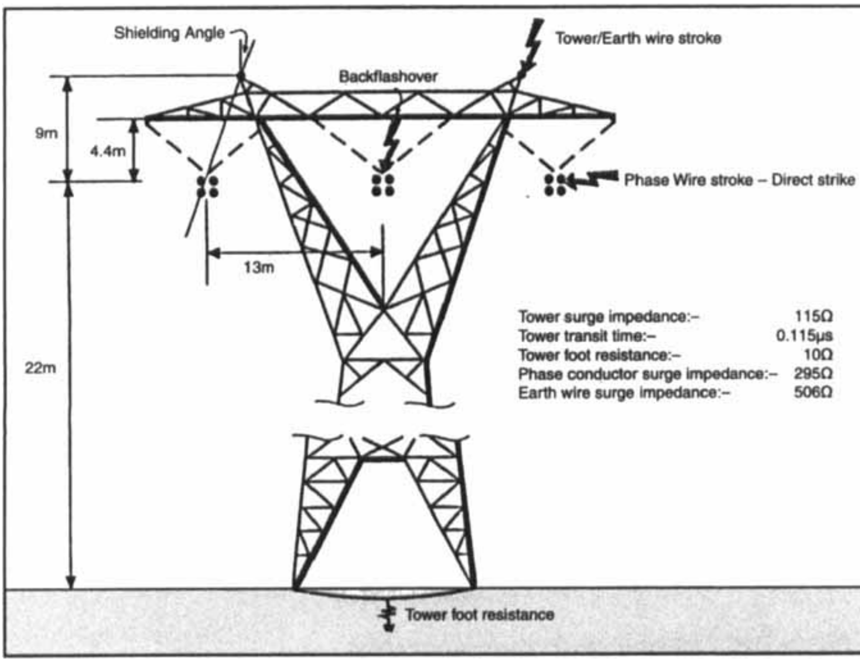


Figure 2.18 Lightning surges

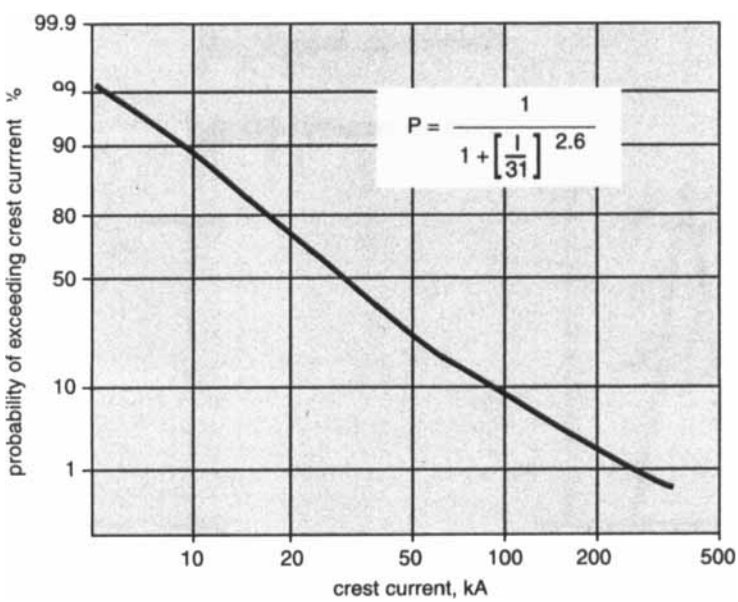


Figure 2.19 Amplitude of lightning stroke current

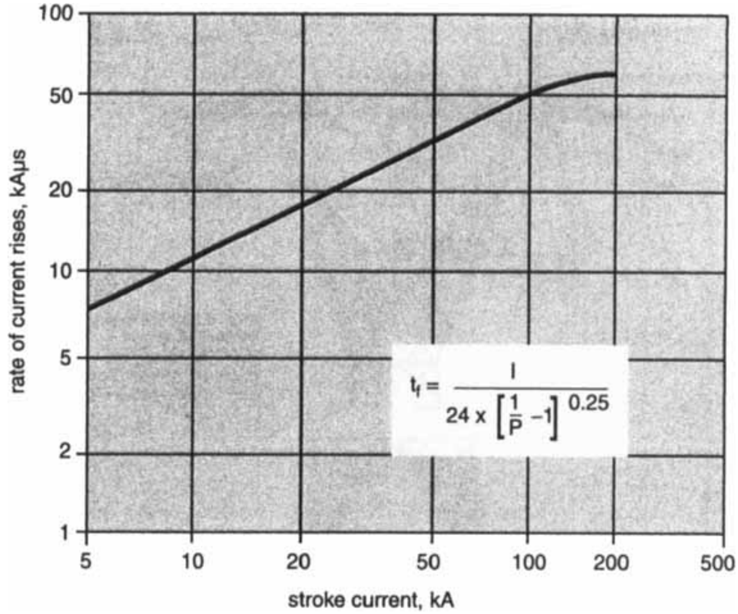


Figure 2.20 Lightning stroke current steepness

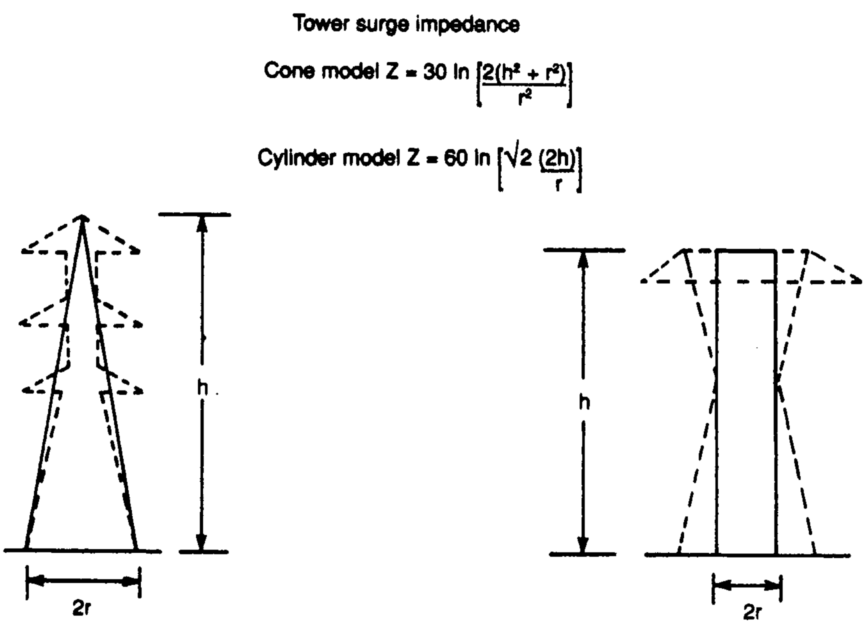


Figure 2.21 Tower surge impedance

base of the tower it dissipates through the tower grounding to earth. An additional voltage is produced at the tower foot which is dependent on the grounding impedance. Figure 2.22 shows typical voltages with the tower travelling wave voltage superimposed on the tower foot voltage. The first voltage pulse width can be estimated by doubling the tower transit time (typically 0.2–0.4 μs). Not all of the tower top voltage will appear across the line insulator because there is some reduction due to the position of the insulator on the cross-arm and also voltage will be mutually coupled from the shield wire to the phase wire. So the voltage that appears across the line insulator co-ordinating gap will be similar but marginally smaller (85%) than the tower top voltage.

Depending on the *V-t* characteristics of the line co-ordinating gap, the backflashover (i.e. from tower to line) may occur near the peak of the voltage pulse or on the surge tail. Test data for line co-ordinating gaps is limited for 'nonstandard' lightning impulse voltages. However, work has been done [13] to establish models of the line gap flashover mechanism. Leader progression models have been proposed which can be used to assess the time to flashover for these waveshapes. Figure 2.23 shows a line gap flashover from a standard 1.2/50 μs lightning impulse voltage and illustrates a 'completed' flashover on one of the gaps with leaders only partially bridging the second gap. It is important to note that as the tower foot resistance is increased the more dominant the tower foot voltage will become to a point where for short towers the voltage waveshape across the line gap will approach that of the 'standard' impulse.

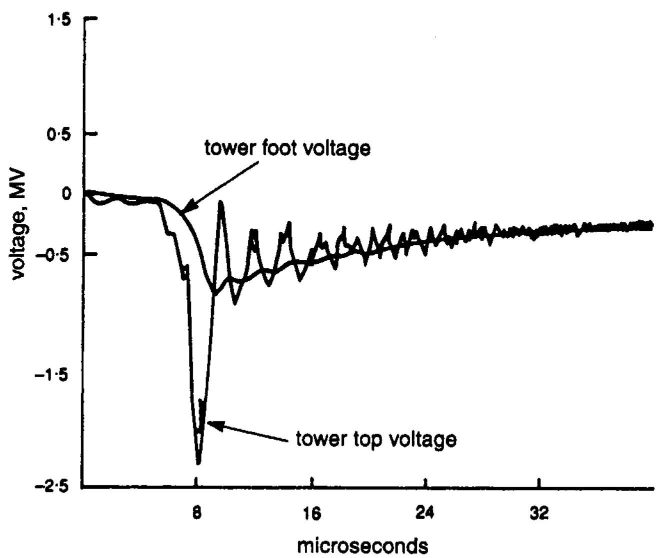


Figure 2.22 Tower voltages

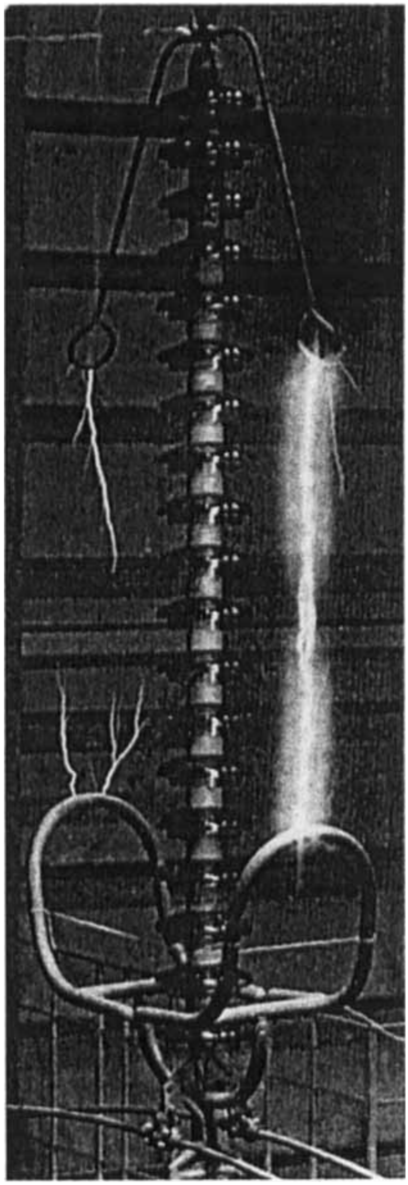


Figure 2.23 Line gap flashover

2.6.2 Direct strike

Most transmission line towers will be equipped with shielding wires. In the tower shown in Figure 2.18 there are two shield wires. The purpose of these wires is to divert the lightning stroke away from the phase wire and thus provide shielding. Any lightning strike which can penetrate the

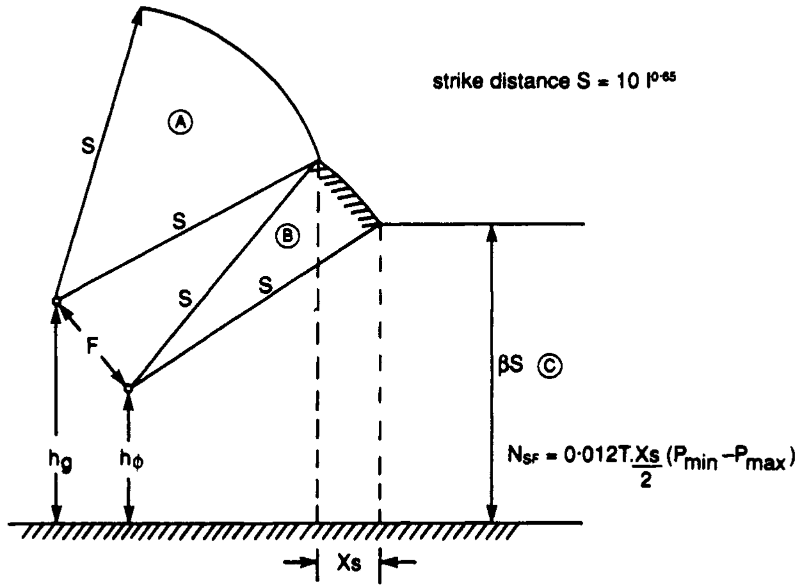


Figure 2.24 Electrogeometric model for shielding failures

	Tower height DC 132 kV	
	30 m	60 m
i_{min}	5 kA	17 kA
I_{max}	28 kA	84 kA
Number of line/tower flashes	19/100 km/yr	39/100 km/yr
Number of shielding failures	0.2/100 km/yr	0.65/100 km/yr
Prob. max E/W stroke current	93 kA	126 kA
Annual thunder days	13	13

Figure 2.25 Lightning performance of transmission lines

shield is termed a 'direct strike' or 'shielding failure'. The electrogeometric model proposed in [11] and shown in Figure 2.24 is a simplified model of the shielding failure mechanism for one shield wire and one phase conductor. As a flash approaches within a certain distance S of the line and earth, it is influenced by what is below it and jumps the distance S to make contact. The distance S is called the strike distance and it is a key concept in the electrogeometric theory. The strike distance is a function of charge and hence current in the channel of the approaching flash. Use of the equation given in Figure 2.24 requires the calculation of S_{MAX} and S_{MIN} which then relate to I_{MAX} and I_{MIN}, the corresponding stroke currents. The probabilities for I_{MAX} and I_{MIN} can then be determined (P_{MAX},P_{MIN}) along with the unshielded width X_s; if $X_s = 0$ then shielding failure will not occur. The objective when designing the line shielding is to minimise X_s. Figure 2.25 compares the results of the electrogeometric model calculations for the shielding performance of two towers with identical conductor and shield wire configuration but are of different heights. A corresponding increase in the number of line flashes and shielding failures is indicated with the taller tower. Also the maximum shielding failure current is three times that for the smaller tower.

For the purpose of insulation co-ordination the direct strike may not warrant further investigation if the transmission line is effectively shielded, particularly in the last 5 km of line approaching the substation. Considering the data from Figure 2.25, a shielding failure rate of 0.2/100 km/year would mean that a direct strike inside the last 5 km of line would occur once in 100 years or a 1 in 3 chance during the life of the substation. When assessing the risk of failure for the substation, however, a sum of all the probabilities for each substation line is required (i.e. six lines would give two surges from direct strikes in the life of the substation).

2.6.3 Attenuation of lightning overvoltage

As the lightning surge travels towards the substation from the struck point the wave front above the corona inception voltage will be retarded by corona loss. Skin effect on the line conductors will cause further attenuation due to the high frequency nature of the surge. It is usual therefore to consider lightning strikes that are 'close-in' (within 3 km) to the substation when assessing surge arrester requirements and the associated risk of failure of the substation.

2.7 Methods of controlling lightning overvoltages

For well shielded transmission lines, the backflashover condition, close to the substation, is of prime concern for determining the location and number of surge arresters required to achieve insulation co-ordination of the substation for lightning surges. The risk of a backflashover can be reduced by keeping the tower foot impedances to a minimum, particularly close to the substation (first five to seven towers). The terminal tower is usually bonded to the substation earth mat and will have a very low grounding impedance (1 ohm). However, the procedure for 'gapping' down on the first three or four towers where line co-ordinating gaps are reduced in an attempt to reduce incoming voltage surges will increase the risk of a 'close-in' backflashover.

2.7.1 Location of surge arresters

Considering the system shown in Figure 2.26, where the transmission line is directly connected to a 420 kV GIS, a computer model can be created to take into account the parameters previously discussed. A transient study would reveal the level of lightning stroke current required to cause a backflashover. Then according to the number of lineflashes/100 km/yr calculated for the transmission line and by using the probability curve for lightning current amplitude, a return time for this stroke current can be assessed (i.e. 1 in 400 yrs, 1 in 10 yrs, etc.) in, say, the first kilometre of the line. The voltage then arriving at the substation can be evaluated and compared with the LIWL for the substation equipment. The open-circuit-breaker condition must be studied here, since if the line circuit-breaker is open the surge voltage will 'double-up' at the open terminal. Various levels of stroke current can be simulated at different tower locations and the resultant substation overvoltages can be assessed. If it is considered that the LIWL of the substation will be exceeded or that there is insufficient margin between the calculated surge levels and the LIWL to produce an acceptable risk, then surge arrester protection must be applied.

The rating of the MOA will have been assessed from TOV requirements, and from the manufacturer's data a surge arrester model can be included in the system model. Repeating the various studies will reveal the protective level of the arrester and from this the safety factor for this system configuration can be assessed [14–18]. IEC 60071 recommends a safety factor of 1.25 for 420 kV equipment (safety factor = LIWL/

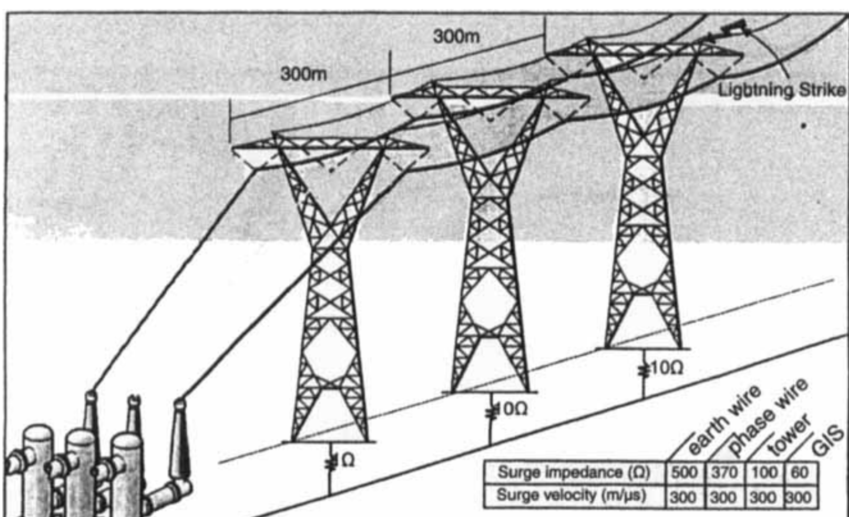


Figure 2.26 System schematic diagram

protective level). The surge arrester current calculated for this condition should be the 'worst' case and can therefore be used to assess the nominal discharge current requirement of the surge arrester (5 kA, 10 kA or 20 kA). (IEC 60091-1 is the international standard for surge arresters [16], and an accompanying guide is available which contains detailed information on the application of surge arresters).

To make full use of the MOA protective level the arrester should be placed as close as possible to the equipment being protected. In the case of the open line circuit-breaker this may well be 10–20 m distance. Dependent on the rate of rise of the surge voltage, a voltage greater than the residual voltage at the surge arrester location will be experienced at the terminals of the open-circuit-breaker. This must be taken into account when assessing the substation overvoltage. Figure 2.27 illustrates the surge voltage profile of the GIS with the line circuit-breaker closed. It shows that additional surge arresters may be required because of the distances involved in the layout of the substation. It then follows that surge arresters have a 'protective length' [14] which is sensitive to the rate of rise of the incoming surge voltage, and this must be taken into consideration when assessing the lighting overvoltage on equipment remote from the surge arrester.

2.8 Conclusions

This chapter has introduced the important concept of insulation co-ordination of high voltage systems. It is vital for any engineer working in, or planning to work in, the electrical power industry to be aware of

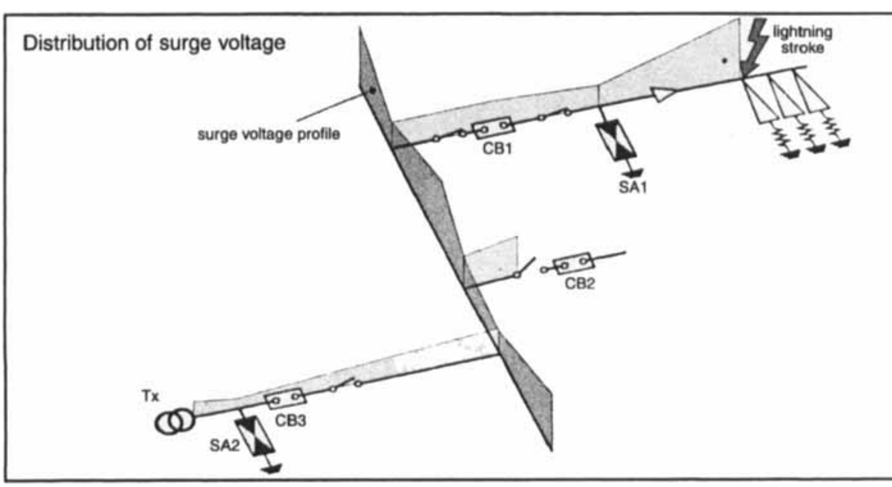


Figure 2.27 Analysis of lightning surge for gas insulated substation

design choices regarding electrical stresses, insulation levels, service performance, etc., together with testing procedures and the importance of IEC standards for a wide range of equipment [19]. These aspects will be considered further in later chapters. The topics have also been discussed in several major publications in recent years (e.g. *Electra*, CIGRE, IEC, IEEE). [For updates visit http://www.global.ihs.com]

The reader should be aware that increasing environmental and aesthetic concerns regarding the utilisation of overhead electrical power transmission lines have resulted in critical evaluation of underground alternatives and, in particular, at opportunities to further reduce the cost ratio between overhead and underground distribution and transmission systems [20]. A joint CIGRE Working Group has been established to evaluate the influence of transient over-voltages on AC cable insulation design. Briefly, if one considers the inherent costs associated with cable systems (cable and accessories) then, by reducing the required withstand capability with improved protection devices and network design philosophy, one could develop a more economic underground system [20]. However, futher insulation coordination studies will be required to determine appropriate safety factors and acceptable failure rates as covered by [14].

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