identification of likely sources of overvoltages and appropriate specification of a surge arrester with a suitable energy absorption capability.

The impact of switching related overvoltages becomes more critical at higher system voltages; therefore typically transmission networks are more susceptible to equipment damage from these overvoltages than compared to range I networks. In practice, the effect of switching overvoltages become important for system nominal with voltages greater than 245 kV (range II).

In range I, the standard insulation level of the equipment is usually so high that protection from slow-front overvoltages is not generally necessary (exceptions are rotating machines). However, the common use of reactive compensation equipment on range I voltages increase the use of surge arresters and the awareness of slow-front overvoltages protection.

The representative overvoltage at the equipment protected by arresters is equal to the switching impulse protection level, because, with the exception of transmission lines, travelling wave effects can be neglected and the voltage at the equipment is equal to that at the arrester. For the phase-to-phase overvoltages, it can be up to twice this value without phase-to-phase arresters.

In the case of surge arrester protection against switching overvoltages, a severe skewing in the statistical distribution of overvoltages takes place. This skew is more pronounced the lower the protection level, as compared to the amplitudes of the prospective slow-front overvoltages. In these situations, small variations of the insulation withstand have a large impact on the risk-of-failure. To cover this effect, it is proposed to make the deterministic coordination factor dependent on the relation of the surge arrester protective level to the 2 % value of the prospective overvoltages, Formulas (6), (7), (8) and (9) [68]:

$$\frac{U_{ps}}{U_{e2}} \leq 0{,}7\,; \quad K_{cd} = 1{,}1 \tag{6}$$

$$0{,}7 < \frac{U_{ps}}{U_{e2}} \leq 1{,}2\,; \quad K_{cd} = 1{,}24 - 0{,}2\frac{U_{ps}}{U_{e2}} \tag{7}$$

$$1{,}2 < \frac{U_{ps}}{U_{e2}}\,; \quad K_{cd} = 1{,}0 \tag{8}$$

and the coordination switching impulse withstand voltage as

$$U_{cw} = K_{cd} \times U_{ps} \tag{9}$$

where

U_{ps} is the switching impulse protective level of the arrester;

U_{e2} is the 2 % value of the prospective slow-front overvoltage amplitude to earth;

U_{cw} is the coordination switching impulse withstand voltage of the equipment;

K_{cd} is the deterministic coordination factor.

NOTE 1 The factor 1,0 to 1,1 takes into account the high frequency of overvoltages with amplitudes equal to the protection level due to the truncation of the overvoltage distribution by the arrester. The lower the protective level the more frequent will be the overvoltages. Due to the uncertainties in the equipment withstand, the margin between the withstand voltage and the protective level should increase with increasing overvoltage frequency to maintain a given risk level.

NOTE 2 If U_{e2} is less than $U_{ps}/1{,}2$ U_{cw} may be calculated without considering the protection by arresters.

6.3.2.7 Protection from fast-front overvoltages

6.3.2.7.1 General

For high voltage arresters in the substations size significantly affects the protection margin where fast-front transients are concerned. Surge arresters cannot adequately protect equipment with large separation distances between line entries and transformer bushings, so typically arresters must be dedicated to critical plant items and additional arresters installed to control the number of overvoltages entering the substation. The coordination lightning impulse withstand voltage can be determined from the following "modified" empirical formula (15) which considers the fundamental characteristics of lightning overvoltage behaviour in stations (see IEC 60071-2).

This modification considers the existence of sizable surge capacitance, C_s, at the line terminal or station entrance which could reduce the steepness of the incoming surge based on line corona distortion factor and accepted failure rate alone as explained in Annex G. The voltage response with capacitance at the line terminal due to the incoming surge with crest, V_s, can be estimated using the formula for the capacitance terminated line where the capacitance, C_s, is charged through the line surge impedance, Z.

Capacitance Terminated Line Voltage:

$$V_c(t) = 2 \times V_s \times \left[1 - e^{-\left(\frac{t}{Z \times C}\right)}\right] \qquad (10)$$

Slope of $V_c(t)$:

$$S = \frac{d}{dt}V_c(t) = \frac{2 \times V_s \times e^{-\left(\frac{t}{Z \times C}\right)}}{Z \times C} \qquad (11)$$

When $(t/(Z \times C)$ is kept constant, the ratio of slopes (steepness factor, f_s), with two different value of capacitances, C_o (equivalent capacitance derived from line corona factor) and C_s (additional capacitance), becomes;

$$f_s = \frac{S_s}{S_0} = \frac{C_0}{(C_0 + C_s)} = \frac{1}{(1 + C_s/C_0)} \qquad (12)$$

where

S_o is steepness due to corona alone;

S_s is steepness with added capacitance.

The estimated reduction in the incoming voltage surge steepness is dependent on the ratio of the initial equivalent capacitance, C_o, and presence of sizable capacitance, C_s, relative to C_o (Annex H). For the incoming voltage steepness estimation, it is convenient to evaluate the slope when constant 0,5 is selected for the exponent $[t/(Z \times C)]$ at 0,5 at which time the capacitor voltage $V_c(t)$=0,5 × $Z \times C$ becomes 0,8 × V_s. Then, the equivalent capacitance value, C_o, can be obtained by equating the time, t_o= 0,5 × $Z \times C_o$, to the same time derived from the same capacitor terminal voltage value (0,8 × V_{crest}) divided by the steepness of the incoming line voltage, S_o, where S_o is estimated using line corona and light speed parameters $(A \times c/2)$ divided by the accepted failure rated distance from station, $(L_{sp}+L_f)$.

$$t_0 = 0{,}5 \times Z \times C_0 = 0{,}8 \times V_s / S_0 \qquad (13)$$

where corona steepness

$$S_0 = (A \times c/2)/(L_{so} + L_f)$$

Thus,equivalent capacitance due to corona

$$C_0 = (1{,}6 \times V_s)/(Z \times S_0) \quad (14)$$

where

$$V_s \approx 1{,}2 \times \text{CFO of line}$$

NOTE Factor f_s is introduced to take into account the current reducing effects of capacitances at the line entrance.

$$U_{cw} = U_{pl} + \frac{A \times f_s}{N} \times \frac{L_t}{L_{sp} + L_f} \quad (15)$$

where

U_{cw} is the coordination lightning impulse withstand voltage;

U_{pl} is the lightning impulse protection level of the surge arrester;

A is the voltage according to Table 3 describing the lightning performance of the overhead line connected to the station;

$f_s = 1 / [1 + C_s/C_o]$ steepness reduction factor with surge capacitance at line terminal

where

C_s is the effective surge capacitance at line terminal, μF

C_o is the equivalent surge capacitance of incoming surge related to corona, μF

C_o ≈ $(0{,}8 \times 1{,}2 \times \text{CFO})/(Z \times S)$ μF

CFO is the line insulation criteria (50 %) flashover voltage, kV

Z is the line surge impedance (~ 300-400 ohms)

S $=(A \times c/2)/(L_{sp} + L_f)$ kV/us

N is the number of lines connected to the substation (N = 1 or N = 2);

L_t is the total length $d + d_1 + d_2 + d_{A,}$ (see Figures 8 and 9);

L_{sp} is the span length;

$L_f = R_a/r$ is the length of the overhead line in front of the station, which gives a rate of lightning events equal to the acceptable failure rate. The right fraction multiplied by A/N is proportional to the steepness of the representative impinging surge. Note that in formulas (15), (16) and (17) consistent units must be used;

R_a is the acceptable failure rate (number of failures per unit time) for the protected equipment;

r is the overhead line outage rate (number of outages per unit time and unit length) per year for a design corresponding to the first kilometre in front of the station. If N = 2, the rates have to be added.

For distribution lines the outage rates are usually large compared to the acceptable failure rates, i.e. the overhead line length L_f in Formula (15) is small and can be neglected. Formula (15) is then simplified to:

$$U_{cw} = U_{pl} + \frac{A \times f_s}{N} \times \frac{L_t}{L_{sp}} \qquad (16)$$

Induced lightning overvoltages need to be considered in distribution systems, where the equipment is not protected against direct lightning strikes to the conductors or against back-flashovers.

Table 3 – Definition of factor *A* in formulas (15) to (17) for various overhead lines

Overhead Line configuration	*A* (kV)
Distribution lines (phase-to-phase flashovers)	
– with earthed cross-arms (flashover to earth at low voltage)	900
– wood-pole lines (flashover to earth at high voltage)	2 700
Transmission lines (single-phase flashover to earth)	
– single conductor	4 500
– double conductor bundle	7 000
– four conductor bundle	11 000
– six and eight conductor bundle	17 000
NOTE The voltages A for distribution lines are lower than that for the single conductor transmission line, because in distribution lines phase-to-phase flashovers or multiple phase-to-earth flashovers occur, thus leading to current sharing, and in case of earthed cross-arms, to a limitation of the incoming surge amplitude.	

The protective zones for fast-front overvoltages of surge arresters installed may also be determined by the acceptable failure rate chosen for a study. IEC 60071-2 suggests values between 0,1 % per year and 0,4 % per year. A typical value of 0,25 % per year is used in the examples of Table 4.

Table 4 – Examples for protective zones calculated by formula (17) for open-air substations

System voltage	Protection level	Withstand voltage		Span	*A*x*fs*	Protective zone L_p					
		rated	Coordination			*r* = 0,1[a]	*r* = 0,5[a]		*r* = 2[a]		*r* = 6[a]
						N = 2	*N* = 1	*N* = 2	*N* = 2	*N* = 2	*N* = 2
kV	kV	kV	kV	m	kV	m	m	m	m	m	m
24	80	125	109	100	2 700	–	–	–	2,4	4,8	3,0
				200	900	–	–	–	10,4	20,8	15,5
123	350	550	478	300	fs=1,0, 4 500	160	23	46	12,0	24	–
					fs=0,5, 2 250	320	46	92	24,0	48	–
420	900	1 425	1 239	400	fs=1, 11 000	180	28	56	16	32	–
					fs=0,5, 5 500	360	56	112	32	64	–

[a] Dimensions in 1 per 100 km and year.

f_s surge capacitance factor e.g. no surge capacitance: f_s = 1,0 , (C_s= 0, C_o estimated from incoming surge),
f_s = 0,5, (when C_s = C_o added)

Formula (15) describes the per unit voltage drop depending on the lightning performance of the overhead line connected to the equipment, on the substation layout and on the adopted acceptable failure rate of the equipment. Using the existing knowledge of the lightning performance of overhead lines and of corona damping effects, the constant A has been determined to obtain agreement between the withstand voltages calculated with Formula (15) and the service experience obtained with protective zones used for a long time (see Table 4). The formula may not be used to determine overvoltage amplitudes for a specific lightning event on the overhead line.

When the rated lightning impulse withstand voltage of the equipment is selected, the protective zone of the arrester can be estimated from Formula (17):

$$L_p = \frac{N}{(A \times f_s)}\left[\left(\frac{U_{rw}}{1,15}\right) - U_{pl}\right](L_{sp} + L_f) \tag{17}$$

where

L_p is the protective zone;

U_{rw} is the required lightning impulse withstand voltage.

Formula (17) indicates that for a given substation, the protective zone increases with:

– increasing difference between rated withstand voltage and protective level;
– decreasing outage rate of the overhead line in front of the station, thus demonstrating the effect of improved shielding by earth wires and reduced tower footing impedance;
– increasing acceptable failure rates, this means that the equipment outside the protective range still may be protected, however with a higher failure rate.

6.3.3 Selection of line surge arresters, LSA

6.3.3.1 General

There are two different designs of LSA: non gapped line arresters, NGLA, or externally gapped line arresters, EGLA, which have somewhat different features making them more or less suitable for certain applications. The NGLA are tested according to IEC 60099-4, while the EGLA are tested according IEC 60099-8. Today's LSA are typically polymer housed which give them significant advantages over porcelain designs for this application. For more information see CIGRÈ 440 [56].

6.3.3.2 Selection of NGLA, non gapped line arresters

6.3.3.2.1 General

Non gapped line arresters are suitable for all system voltages and for protection against both lightning and/or switching related phenomena.

The selection of NGLA for line protection differs only slightly from typical arrester selections. The most significant difference is the use of disconnectors for NGLA also for system voltages above distribution systems. The following iterative procedure, shown in the flow diagram of Figure 21, is recommended for the selection of NGLA:

– determine the continuous operating voltage of the arrester with respect to the highest system operating voltage;
– determine the rated voltage of the arrester with respect to the temporary overvoltages;
– estimate the magnitudes, charge (or related arrester energy) and probability of the expected lightning discharge currents through the arrester, determine the transmission line discharge requirements and select the nominal discharge current, the high current impulse value, the line discharge class and the lightning impulse discharge capability of the arrester considering an acceptable arrester failure rate;

NOTE Lightning discharge currents and related discharge energy may be significantly higher than for station applications in particular in the case of unshielded lines. Switching impulse currents may be lower.

– select the short-circuit rating with respect to the expected fault current;
– select a surge arrester that fulfils the above requirements;
– determine the lightning and switching impulse protection characteristics of the arrester;
– locate the arrester as close as possible to the insulators to be protected with consideration to sufficient clearances in the event of arrester overloading and disconnector operation;
– determine the coordination switching impulse withstand voltage of the protected equipment taking into account the representative slow-front overvoltages and system layout;
– determine the coordination lightning impulse withstand voltage considering:
  • the representative lightning current surge as determined by the lightning performance of the overhead line to which the arrester is connected (ground flash density, strike incidence to the line, tower footing resistance etc.) and the acceptable flashover rate of the protected insulation;
  • the line layout;
  • the length of connection leads between surge arrester and protected insulation;
– determine the rated insulation level of the equipment from IEC 60071;
– if a lower rated insulation level of the equipment is desired, then a lower rated voltage, a higher nominal discharge current, a higher line discharge class, a higher lightning impulse discharge capability, a different arrester design or a reduced length of connection leads between arrester and protected insulation should be investigated;

NOTE 1 A lower rated voltage may affect the service reliability of the arresters, due to the higher specific voltage stress under COV.

NOTE 2 Insulation levels for lines may differ from the levels given in IEC 60071.

NOTE 3 The normal case may be that the arresters are to be installed on an existing line. The coordination switching and lightning impulse withstand voltages are then compared with the existing insulation levels of the line.

– the risk of arrester overloading due to lightning discharges should be considered and taken into account in the calculated flashover and outage rate of the line.

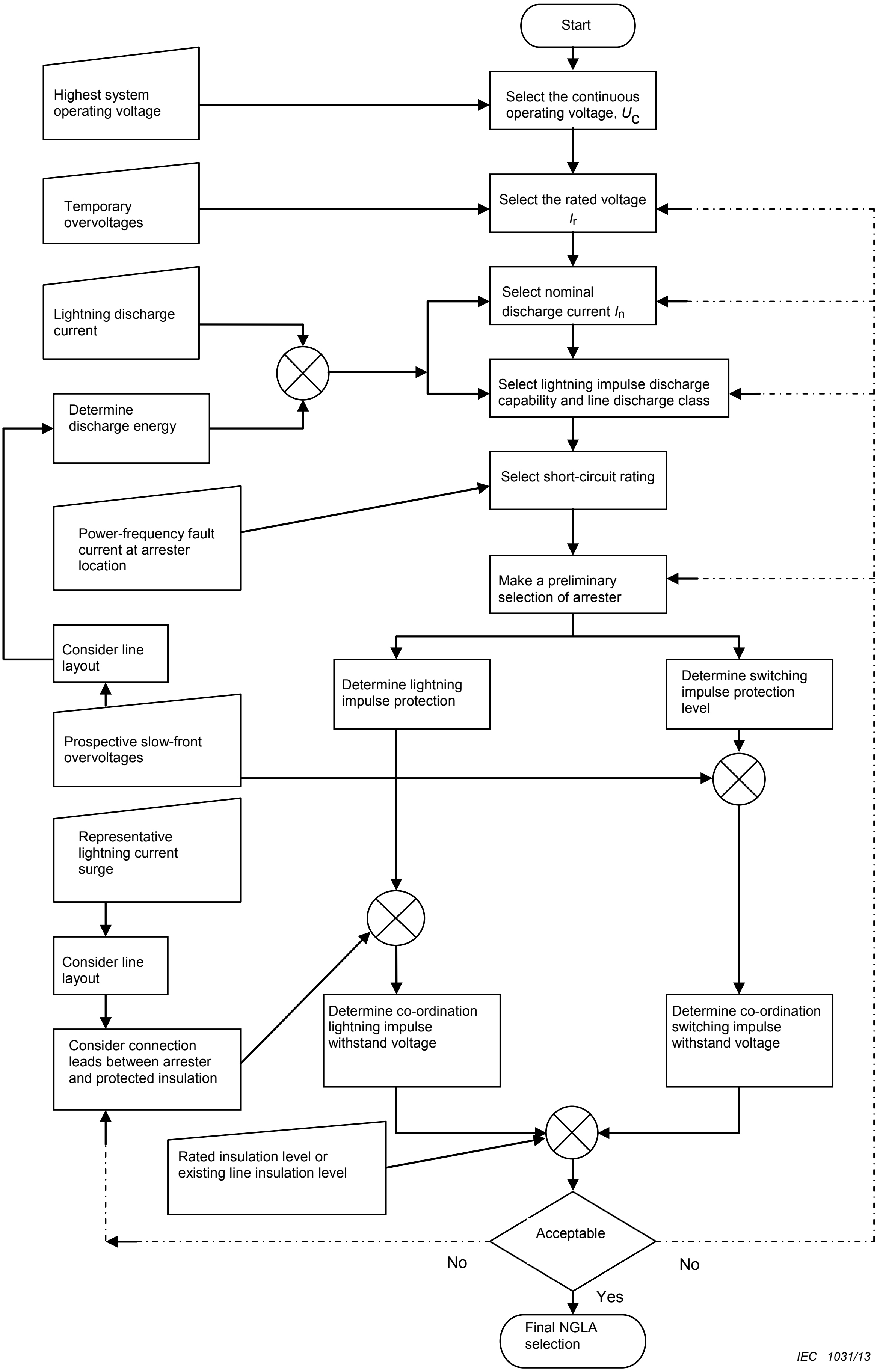

Figure 21 – Flow diagram for the selection of NGLA

6.3.3.2.2 Rated voltage

The rated voltage shall be selected so that the lightning and switching surge protective levels are coordinated below the LIWV, and SIWV of the line insulation respectively. Selection of rated voltage is not especially crucial, as there usually is an ample margin between LIWV of line insulation and protective levels, and there is no benefit of extra protective margins. Thus it is not recommended to choose the lowest possible characteristics, as this will increase the risk that these arresters may be stressed by unnecessary high power frequency overvoltages. This is typically done by selecting a higher rated voltage and/or a lower IEC line discharge class of the NGLA than for the substation arresters. Such a selection also ensures that the arresters are not unnecessarily stressed by high switching energies or capacitor discharges, which should be handled by the substation arresters.

6.3.3.2.3 Arrester class and energy requirements

NGLA are selected both with respect to their arrester classification and for NGLA with a rated voltage higher than 52 kV also from their lightning impulse discharge capability in Annex N of IEC 60099-4:2009. NGLA on shielded lines typically has a nominal discharge current of 5 kA or 10 kA according to IEC with line discharge classes 1 to 3, depending on their application.

For NGLA installed for lightning protection on unshielded lines a nominal discharge current of 10 kA or 20 kA according to IEC with line discharge classes 2 to 4 may be used depending on the isokeraunic levels (thunder days/year, T_D) and expected outage rate. There are special software available on the market which will give guidance for the dissipated charge/energy from lightning strokes.

NGLA for protection of switching overvoltages are selected to have the same or in many cases one IEC line discharge class lower than what the substation arresters have, due to that for longer lines the NGLA are installed around the midpoint reducing the line length for the involved NGLA. Typically a nominal discharge current of 10 kA or 20 kA according to IEC with line discharge classes 3 to 5 may be used.

6.3.3.2.4 Fault clearing and disconnectors

Disconnectors are used to facilitate fast reclosing as NGLA are connected directly across the line insulators which are self-restoring. Disconnectors are usually not permitted to disconnect high voltage substation arresters automatically in the event of an arrester failure since the insulation of the substation equipment is generally not self-restoring and should not be re-switched in without protection.

These disconnectors in series with the NGLA also serve as indicators making it simple to find overloaded NGLA with visual inspection.

These disconnectors will have somewhat different requirements from the ones used for distribution arresters in that they must match the energy handling capabilities of the NGLA. Therefore these disconnectors must be capable of withstanding both higher impulse currents as well as longer duration impulses compared to disconnectors for distribution arresters; in fact the disconnectors must pass all the type tests that the NGLA is capable of. The crucial requirements of the disconnector are to verify that it does not operate unless the NGLA is overloaded and that it operates quickly enough. For unearthed systems without shield wires, having a very low short-circuit current out on the lines, such as only a few tens of Amps, this leads to conflicting requirements of the disconnectors.

The disconnector device is often mechanically weaker than the rest of the installation. Hence, the conductor connecting the NGLA to earth or the phase conductor must be sufficiently long to ensure that the movements of the arresters and/or the transmission line will not risk that the disconnector device may break off by mechanical fatigue.

The tower with an overloaded gapless line arrester shall after the disconnector operation preferably have LIWV and SIWV as prior to the line arrester installation, as it may take some time before failed NGLA can be replaced.

6.3.3.2.5 Applications of NGLA

NGLA are suitable for all mentioned applications mentioned in 6.2.4, as they can be selected to protect against both lightning and switching overvoltages.

However, in areas with high ground flash density, one should make sure that disconnectors with proper operation characteristics are selected for the application of NGLA for unshielded overhead lines on compensated/non directly earthed high voltage systems with earth fault currents below 100 A.

With NGLA installed on every tower it is today possible to design compact transmission lines with significantly smaller clearances than what is traditionally used, if pollution is not the limiting factor of line insulation. NGLA can also be used to upgrade existing system voltages using existing towers and lines, especially for old not commonly used system voltages. For this application NGLA can be used either on the top phase(s) as a substitute for shield wires in areas with moderate ground flash density or on all three phases together with shield wires. NGLA are recommended as both fast-front and slow-front overvoltages may be critical.

By locating NGLA on all phases of the towers closest to a substation the incidence of back-flashovers near the substation can be more or less eliminated. This results in a reduction of steepness and amplitude of incoming surges. This improves the protection performance of the station arresters for air-insulated substations, and may eliminate the need for metal-enclosed arresters even for large GIS. For this application NGLA shall be used, as the incoming overvoltage should have both reduced magnitudes and as slow rise time as possible when entering the substation. This will increase the minimum protection distance inside the GIS. Even parallel columns may then be the most economical solution. These parallel columns of the same rated voltage do not have to be matched with respect to current sharing as they are only for reducing the protection levels.

6.3.3.3 Selection of EGLA, externally gapped line arresters

6.3.3.3.1 General

One difference from NGLA is that the series varistor unit (SVU) of the EGLA is not continuously exposed to the system voltage. Hence the selection of the rated voltage of EGLA will differ from NGLA. Another important feature is the coordination of its gap characteristics with the LIWV and SIWV of the protected line insulation.

The following iterative procedure, shown in the flow diagram of Figure 22, is recommended for the selection of EGLA:

- determine the rated voltage of the arrester with respect to the highest system operating voltage and temporary overvoltage during spark over operations;
- estimate the magnitudes, charge (or related arrester energy) and probability of the expected lightning discharge currents through the arrester, select the nominal discharge current, the high current impulse value and the lightning impulse discharge capability of the arrester considering an acceptable arrester failure rate;
- select the short-circuit rating with respect to the expected fault current;
- select a surge arrester that fulfils the above requirements;
- determine the insulation withstand of EGLA (with shorted SVU) with respect to maximum slow-front overvoltages on the system;
- determine the lightning impulse protection characteristics of the arrester comprising the spark over voltage for fast-front, and standard lightning impulse and residual voltages for the nominal discharge and high current;

– determine the coordination lightning impulse withstand voltage considering:
  - the representative lightning current surge as determined by the lightning performance of the overhead line to which the arrester is connected (ground flash density, strike incidence to the line, tower footing resistance etc.) and the acceptable flashover rate of the protected insulation;
  - the line layout;

NOTE 1 A lower rated voltage may reduce the service reliability of the arresters.

NOTE 2 Insulation levels for lines may differ from the levels given in IEC 60071.

NOTE 3 The normal case may be that the arresters are to be installed on an existing line. The coordination lightning impulse withstand voltage is then compared with the existing insulation level of the line.

– the risk of arrester overloading due to lightning discharges should be considered and taken into account in the calculated flashover and outage rate of the line;

– EGLA is considered to be installed directly in parallel with the insulator assembly. The effect of connection leads shall be considered in the residual voltages given for the arrester as per IEC 60099-8.