Introduction
When lightning surges enter a station, reflections occur and oscillations are set up due to the capacitance of the station apparatus and inductance of busbars and connection leads. For steep incoming surges, the difference in voltage shape and amplitude at different locations in the station will be significant as illustrated in Figure 1.

As a station should be designed for a low probability of failure, it is only steep incoming surges which are of interest. Thus the protection of a substation against lightning surges is not only a question of which arrester to choose. It is even more important to determine the number and location of arresters needed in order to obtain an adequate protection.

For a full treatment of the problem many parameters must be considered concerning probability — distribution of lightning currents, station layout, power frequency voltage, grounding, shield wires, protection levels and connection leads of surge arrester, insulation levels etc.

In view of the complexity of the problem, practical engineering has long been based mainly on rules of thumb, or on simplified formulas, which often disregard many of the important parameters.

With the present improved knowledge of lightning as well as the existence of efficient computer programs, however, it is now possible to give much more accurate guidance for protection against lightning.

The aim of this paper is to give such guidance in a simple and practical way concerning the three main topics in station protection; namely

- Protection of open air substations
- Protection of GIS
- Protection of open line breakers

However, the final choice must always be left to the system engineer, who has to take into account additional parameters such as the importance of the station and the cost of a failure compared with the cost of improved protection, and who must decide upon an acceptable level of risk.

All the diagrams presented are based on "common choice" arresters for a specific system voltage level.

The "common choice" arresters as well as details of arrester characteristics are found in the primary reference document "Selection guide for ABB HV Surge arrester" (Ref. [8]) and in the corresponding surge arrester catalogues.
Protection of open air substations

Protective distances

When there are connection leads to the surge arrester and/or a distance between arrester and the equipment to be protected, then the protected object will be subjected to a higher overvoltage than could be estimated from the surge arrester characteristics only.

The traditionally used formula to estimate this separation effect:

\[ U = U_a + \left( \frac{2 \times S \times L}{v} \right) \]  

where

- \( U_a \) = arrester residual voltage
- \( S' \) = steepness of incoming surge
- \( L \) = distance between arrester and protected object (sometimes including connection leads)
- \( v \) = velocity of incoming surge
- \( U \) = voltage at protected object

has three main weaknesses:

- Any capacitance of the protected object is disregarded
- The effect of the instantaneous value of the power frequency voltage is not considered.
- The true voltage-current characteristics of the arrester including frequency dependence are not used.

Thus, if the margin between the arrester protective level and LIWL of protected object is not large, the use of the simplified formula is not recommended.

To provide a more accurate guidance, some general curves have been established regarding protective distances for ABB surge arresters as shown in Figures 2 to 9.

The curves are based on a great number of computer calculations which take into account what is missing in the simplified formula. Four voltage levels, 145 to 420 kV, are specifically treated. For any other voltages between 120 and 420 kV not directly found in Figures 2 to 9, the figure which best agrees with the actual system voltage can be used with good accuracy.

As the protective distance, among other parameters, is also a function of the capacitance of the protected object, the curves are presented in form of shaded areas covering a variation in capacitance from 0 to 4 nF. The exact value of the capacitance is often not known in which case the worst case must be assumed. 0 to 4 nF will be sufficient to cover most transformers and also the case with an open bus end.

In each case the overvoltage amplitude (at a particular distance from the arrester) is given in relation to the residual voltage at 10 kA (8/20 \( \mu \)s) – as per the catalogue values.

Note! The shaded areas are presented to give an idea of the variation as function of capacitance. The true curves for certain capacitances may cross each other why it can not be assumed that the lower part and top part correspond to 0 and 4 nF respectively.
Example

System voltage 245 kV, incoming surge 1200 kV/µs, "common choice" arrester EXLIM P192-AH245 having a rated voltage of 192 kV and residual voltage at 10 kA (8/20 µs) of 442 kV.

The insulation level of the transformer has been specified as 1050 kV. Dividing 1050 with 442, gives 2.38 in p.u. of arrester 10 kA residual voltage and, applying Figure 4, indicates that the arrester can be installed up to 57 m from the transformer. This assumes that up to 1050 kV is accepted at the transformer i.e. no extra margin is allowed.

The final choice of protective distance thus depends also upon the design safety margin.

Steepness of incoming surge

Steepnesses of 1200 and 2000 kV/µs have been well established in standards and practical insulation co-ordination studies for a long time and have also been taken, therefore, as reference surge steepnesses in this paper.

It is mainly the risk of backflashes or shielding penetration close to the station which have to be determined. The difference in strike rates lead to either 1200 or 2000 kV/µs. Guidance for the choice between the two steepnesses is given in the flow chart in Figure 11 – as discussed further under "Protection of GIS stations" below.

Line entrance arrester

If, due to any reason, it is impossible to install the station arrester as close to important equipment as ideally necessary, the protective distance of the station arrester may be improved by installing an additional arrester at the incoming line. This arrester also fulfils a second function as protection for an open line breaker.

The efficiency of an additional arrester is exemplified in Figure 10 for a 362 kV station, incoming surge 2000 kV/µs and a second arrester 50 m in front of the station arrester. The protective distance should be compared with distances in Figure 7 for a single arrester. As can be seen, the protection distances are almost doubled.

Figure 11. Choice of incoming surge steepness
Protection of GIS stations

With the growing proliferation of high-voltage gas-insulated substations (GIS) in modern power systems, it has become increasingly important that high reliability of such GIS installations also be ensured through suitable surge arrester positioning and correct insulation co-ordination.

In practice, the lightning overvoltage mechanism is complex and involves consideration of a number of statistical aspects — including variations in lightning parameters, strike location and overvoltage mechanism (e.g. backflash and/or shielding penetration).

This topic has been actively studied within CIGRE during recent years (Ref. [1-3]), and it is found that practical application situations can often be usefully analysed using simplified approaches. In the main, these involve determination of a “reference” incoming overvoltage (i.e. the impinging surge), having an amplitude typically in the range 1.0 - 1.6 times the incoming line LIWL; with the parameters of this surge (steepness and peak value) being set principally by the lightning performance of the incoming line itself (i.e. by the risk of lightning strike, line insulation level and shielding, quality of earthing etc).

As an approximate guide, Figures 12-19 present the results of computer analysis of the protective distances associated with sample GIS and ZnO surge arrester configurations for two alternative combinations of incoming surge amplitude and steepness (either 1200 kV/µs or 2000 kV/µs). The arresters are assumed to be positioned outside the GIS.

In practical applications, as a first approximation, the appropriate choice of incoming surge steepness may be assessed from the flow diagram of Figure 11. This figure attempts to take account of those factors which have the most influence in evaluation of the statistical risk of failure of a GIS installation against incoming lightning surges; namely

- system voltage level (i.e. line LIWL).
- regional incidence of lightning; here expressed in annual ground flash density $N_g$, where $N_g$ may be approximated from

$$N_g = 0.04 \times T_d^{1.25}$$

$N_g$ = flashes per sq. km and year,
$T_d$ = annual number of thunderstorm days.
- average transmission tower footing resistance, especially along the last few km of line into the GIS station.
- degree of exposure of individual towers close to the station, and the quality of the transmission line shielding design (e.g. as per Ref. [4]).
- the extent to which the GIS may be operated in critical configurations, such as “open-breaker”, or the degree of available redundancy (multiple busbar/breaker schemes), and/or the extent to which system operations may tolerate a GIS fault.

Estimation of protective distances from Figures 12 to 19 — based on steepnesses chosen via Figure 11 — can be a useful guide to first analysis of simple surge arrester/GIS installations.

![Figure 12. 145 kV system](image1)

![Figure 13. 145 kV system](image2)

![Figure 14. 245 kV system](image3)

![Figure 15. 245 kV system](image4)

![Figure 16. 362 kV system](image5)

![Figure 17. 362 kV system](image6)
Arresters within GIS

In most cases, a single set of well qualified arresters installed as close as possible to the GIS entrance (i.e. within a few meters) and with short connection leads, will protect a comparatively long GIS bus.

It is, therefore, not usually a question of choice between a metal-enclosed surge arrester within the GIS or a conventional porcelain type arrester at the GIS entrance but whether a GIS arrester is needed in addition.

Provision of a single GIS arrester set only will provide good protection at its location, but any open disconnecting switch and breaker between the arrester and the GIS entrance could be left unprotected.

In Figures 20 and 21, overvoltage protection with and without a GIS arrester are compared for a 145 kV station with an incoming surge of 2000 kV/μs. In both cases an arrester is installed at the GIS entrance and a 120 m GIS bus is assumed between the entrance and the transformer, which is represented by a capacitance of 2 nF.

The relative advantage of the additional GIS arrester is clearly demonstrated.
Protection of open breaker

In approximately 55% of all ground flash cases (Ref. [7]), the first lightning stroke will be followed by one or more successive strokes. The first stroke may lead to a single-phase or multi-phase ground fault on a line, causing the relay protection to operate and to open the line breakers.

If then a rapid following stroke hits the line, the lightning surge may reach the breaker in open position before the breaker has fully recovered its dielectric strength across the contacts. A restrike and possible breaker damage may occur.

The station arrester cannot protect the breaker in this case. A rod-gap on the line side of the breaker will also give poor protection, due to the delay in spark-over on steep voltage surges and due to the "high" spark-over setting which is necessary to avoid unwanted operations of the gap.

This general situation is illustrated in Figures 22 and 23 for a typical shielding penetration lightning stroke on a 500 kV system. Figure 23 shows in addition to the limited "protection" given by rod-gap, the superior protection which can be obtained with a ZnO arrester on the line side of the breaker.

Such an additional breaker arrester will also improve the overall overvoltage protection of the station. This may be best illustrated by a statistical analysis, as shown in Figure 24, based on full Monte-Carlo technique to determine the overvoltage distribution with and without a breaker arrester. As shown, the arrester at the breaker markedly decreases the risk of flashover to ground at the breaker.

Figure 22. Overvoltage at line breaker without special breaker protection.

Figure 23. Overvoltage at line breaker protected by rod-gap or ZnO arrester.

Figure 24. Overvoltage distribution at the breaker with only one arrester located at the transformer 50 m behind the breaker. As a comparison the dashed curve indicates the overvoltage distribution when an additional arrester is installed 5 m in front of the breaker. (145 kV station, surge arresters type EXLIM Q with rated voltage 120 kV)
Open air stations

1. Determine design safety margin for station and equipment insulation (typically 20% – as given by IEC 71-1976).
2. Determine incoming transmission line and "environmental" parameters, including average tower earth resistances, quality of shielding against lightning, local thunderstorm day level (or regional lightning flash density), and the extent to which you can tolerate a system outage.
3. Based on these parameters, determine the average incoming surge steepness from Figure 11.
4. Use this steepness in Figures 2 to 9 to estimate the available protection distance from the planned ZnO arrester location (taking the overvoltage safety margin into account) – based upon "common-choice" arrester in accordance with the Selection Guide.
5. If larger protective distances are required for the station, re-arrange the number of ZnO arresters and positioning (again in accordance with step 4 above) and/or consider using a more qualified arrester such that all critical locations are adequately protected within the design safety margin.
6. Pay particular attention to line entrance and open-breaker contingencies – bearing in mind that the risk of circuit-breaker flashover (on a subsequent stroke) is highest just when the breaker is already actively clearing a lightning fault. If the system protection and/or fault tolerance/stability considerations cannot tolerate the risk of such a double contingency outage, then install an additional ZnO arrester for the open breaker protection.

GIS stations

1. Determine design safety margin for station and equipment insulation (typically 20% – as given by IEC 71-1976).
2. Determine incoming transmission line and "environmental" parameters, including average tower earth resistances, quality of shielding against lightning, local thunderstorm day level (or regional lightning flash density), and the extent to which you can tolerate a system outage.
3. Based on these parameters, determine the average incoming surge steepness from Figure 11.
4. Use this steepnesses in Figures 12 to 19 to estimate the available protection distance for a ZnO arrester located at the station entrance (taking the overvoltage safety margin into account) – based upon "common-choice" arrester in accordance with the Selection Guide.
5. If larger protective distances are required for the station, re-arrange the number and positioning of ZnO arresters – including new additional arresters inside the GIS – (again in accordance with step 4 above) and/or consider using a more qualified arrester such that all critical locations are adequately protected within the design safety margin.
6. As before, pay particular attention to any critical open-breaker or open disconnecter contingencies and, if necessary, repeat steps 4 and 5 until all important station operational contingencies (i.e. practical operating layout alternatives) are adequately protected.
Concluding remarks

A ZnO surge arrester, compared with other station equipment, such as breakers and transformers, is a relatively low cost item; typical cost for the arresters in a common station would be less than five percent of the total cost.

It is usually acceptable therefore to base the selection of protection levels, number and positioning of the arresters on general curves as long as the assumptions behind the curves and guidelines are generally conservative, i.e. give results on the safe side.

This paper sets out to provide basic information which can be directly used in the majority of cases. Simple radial configurations of the stations have been assumed, which in general give higher overvoltages at the protected equipment than more complex stations with additional lines and busbars even if the opposite may be true in rare cases. The effectiveness of additional arresters at breakers, line-entrance and within GIS have been pointed out as simple solutions when a single arrester protection seems insufficient.

In even more complex situations, however, or where more extreme parameters are involved (e.g. in relation to Figure 11) or in especially important installations, money can certainly be saved through an optimal arrangement of arresters. For such cases it is recommended that a detailed computer analysis rather be carried out for the specific station/transmission line configuration, based on the relevant parameters of the real situation. ABB is readily able to carry out such studies, using optimised computer programs and taking full account of the modern analytical procedures being developed within organisations such as CIGRE and IEEE.

References