

Points to consider regarding the insulation coordination of GIS substations with cable connections to overhead lines

M. M. Osborne, A. Xemard, L. Prikler, J. A. Martinez

Abstract. Gas Insulated Switchgear (GIS) when coupled with short cables complicates insulation co-ordination practice particularly regarding fast front transients. The impact of an over-voltage in GIS can be worse than air insulated switchgear (AIS), since a flashover in solid insulation or GIS can result in permanent faults which require long term outages before repairs can be made.

Although, a number of insulation coordination studies have discussed controlling over-voltages due to lightning and switching in Gas Insulated Switchgear (GIS) and transformers, not many deal with the additional complexity raised when cables are used to connect overhead lines to the new equipment.

The paper reports on aspects of work being done within the CIGRE Working Group on Insulation Coordination. (C4.301). An introduction is provided to the sensitivities which affect the magnitude of fast front transients occurring in a typical arrangement including overhead-lines connected to GIS and transformers using short cable sections. This considers factors including lightning, cable length, tower footing impedance and substation running arrangements. Generic sensitivities will be examined for a 400kV circuit, using studies carried out in EMTP to establish the nature of these over-voltages within the substation and the effectiveness of control methods to mitigate their impact.

Keywords: GIS, Insulated Cables, Surge Arresters, Insulation Coordination, Lightning Overvoltages, Modelling, simulation, EMTP.

I. INTRODUCTION

The asset replacement of Air Insulated Switchgear (AIS) substations by GIS at all levels is a challenge facing many mature utilities. Among the solutions, is to build offline, using compact or GIS technology and then cable into the existing

lines. This provides many benefits by reducing land take, shortening the project time and improving reliability and construction safety.

The CIGRE joint working group 33/23.12 presented a detailed study on the insulation coordination of GIS [1]. It conducted an extensive survey based on the 30 years return-of-failure of 11 utilities. This survey showed that the mean number of dielectric failures per 100-GIS bay-years increases with the rated voltage (Table 1). The survey suggests that 61% of the failures occurred at nominal voltage and 39 % occurred for AC overvoltage and / or switching. Only one failure due to lightning had been reported.

Voltage levels	Dielectric failures per 100-bay years
125-145 kV	0.26
245 kV	0.67
420 kV	1.8
550 kV	3.9

Table 1. Number of GIS dielectric failures per 100 bay years

This survey seems to indicate that fast-front-over-voltages are not a major concern for GIS. In fact, with the insulation coordination rules applied today in utilities it may even be tempting to reduce the Lightning Withstand Voltage of GIS or to limit the number of surge arresters in use in GIS configuration.

On the other hand, the insulation coordination of GIS connected to an overhead line through an underground cable poses a particular problem. IEC 60071-2 considers that generally in such a configuration it is required to select the higher standard rated lightning impulse voltage from IEC 60071-2 and to install surge arresters at the line cable junction. However, in this particular case there seems to be merit in checking if additional insulation rules might need to be specified. The work underway within CIGRE WG C4 301 'Insulation Coordination' aims to address this issue.

The compact nature of GIS, when coupled with short sections of cable, complicates insulation co-ordination practice. The impact of a fast front transient can be worse, since a flashover in solid insulation or GIS can result in permanent faults which require long term outages before repairs can be made. Although, there are a number of insulation coordination studies which discuss controlling over-voltages due to lightning and switching in Gas Insulated Switchgear (GIS) and transformers, not many deal with the additional complexity raised when cables are used to connect

Alain Xemard is with EdF, Clamart, Paris, France (email : alain.xemard@edf.fr).

Mark M. Osborne is with National Grid, Warwick Technology Park, Gallows Hill, Warwick, CV34 6DA, UK (email: mark.osborne@uk.ngrid.com).

Juan A. Martinez is with the Dept. d'Enginyeria Elèctrica, Universitat Politècnica de Catalunya, Barcelona, Spain (e-mail: jamv@ieec.org).

László Prikler is with the Department of Electric Power Engineering, University of Budapest, Budapest, Hungary (email: prikler@vmt.bme.hu)

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overhead lines to the new equipment [27].

This paper attempts to provide an insight for utilities into the significant factors for fast front transients which need to be considered regarding substation insulation coordination. The example of a 400 kV GIS connected to a double-circuit overhead line by an underground cable is used to illustrate the issues.

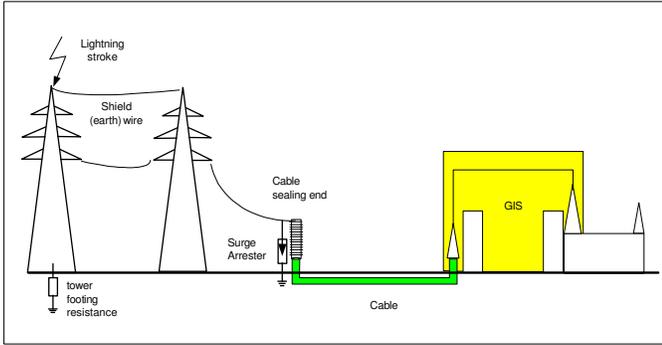


Figure 1. Typical GIS substation entry configuration

II. MODELLING

Modelling guidelines for lightning studies have been presented in several publications [2], [3], [4], [24] and the following paragraphs summarise the key issues.

A. Overhead line

The transmission line (shield wires and phase conductors) is modeled by means of 3 or 4 spans from the transition overhead line – insulated cable, plus a termination to avoid reflections that could affect the simulated overvoltages around the point of impact. Each span is represented as a multi-phase untransposed distributed-parameter line section, whose parameters can be either calculated at a given frequency (usually 500 kHz [24]) or considered frequency-dependent. A short line section that connects the last tower to the surge arresters and to the insulated cable will have to be usually included in the model; its representation will be based on the same model that for the rest of the line, although the most accurate representation should be based on a *non-uniform* model.

- 1) The line termination can be represented by means of a long enough section, whose parameters are calculated as for the line spans, or by a resistance matrix that matches the line spans. Note that this last option is in general selected when the parameters are calculated at a constant frequency.
- 2) Towers are represented as an ideal single conductor distributed-parameter line. However more complex models can be also considered [5], and its application is advisable for towers taller than 50 meters [6].
- 3) Phase voltages at the instant at which the lightning stroke impacts the line might be included, and their values are sometimes deduced by randomly determining a phase reference angle.

- 4) The lightning stroke is represented as an ideal current source (infinite parallel impedance) whose parameters, as well as its polarity, are determined according to the distribution density functions recommended in the literature [6] - [10]. The characteristics of the impulse are best considered as the CIGRE concave wave shape or a double ramp [4].
- 5) The representation of insulator strings can rely on the application of the leader progression model [6], [10], [11]. The leader propagation can be deduced from the following equation

$$\frac{dl}{dt} = k_l V(t) \left[\frac{V(t)}{g-l} - E_{l0} \right] \quad (1)$$

where $V(t)$ is the voltage across the gap, g is the gap length, l is the leader length, E_{l0} is the critical leader inception gradient, and k_l is a leader coefficient. For a more detailed description of this model see also [12]. Other models like the equal area criteria model are also used.

- 6) The footing impedance [25] can be represented as either a constant resistance or a non-linear resistance whose value is approximated by the following expression [6], [13]

$$R_T = \frac{R_0}{\sqrt{1 + I/I_g}} \quad \left(I_g = \frac{E_0 \rho}{2\pi R_0^2} \right) \quad (2)$$

where R_0 is the footing resistance at low current and low frequency, I is the peak value of the stroke current through the resistance, and I_g is the limiting current to initiate sufficient soil ionization, being ρ the soil resistivity (ohm-m) and E_0 the soil ionization gradient (400 kV/m) [14].

B. Insulated cable

The most accurate representation of an insulated cable in lightning studies is a frequency-dependent distributed-parameter model. However, for short lengths a simple model (without cross-bonding and) with constant parameters can be also considered. Given the fast front transients that are generated with the impact of a lightning stroke, the calculation of parameters at a frequency between 400 and 500 kHz will suffice. Calculation of parameters at a lower frequency, or even at a power frequency (50/60 Hz) can be also used, but it will provide conservative results (i.e. less damping) [28].

C. Gas insulated switchgear (GIS)

The most accurate representation of a GIS for the present study can be performed following the guidelines suggested for very fast front transients [2], [3], [15]. The GIS model should include most substation equipment (ducts, elbows, spacers, arresters, bushings, etc.). However, many of these components

will have a negligible effect on lightning transients if GIS is coupled to overhead lines through short cables. A conservative approach could consist of representing the GIS by a single duct in which waves propagate at the speed of light, whose length is the longest distance from the transition insulated cable – GIS to the further open terminal, and whose surge impedance is deduced from geometry. Most actual GIS are based on single-phase ducts. Modelling guidelines for three-phase GIS have been proposed in [16].

D. Surge Arrester

The surge arrester model has to exhibit a nonlinear behavior. The IEEE WG [17] has provided guidelines, although other models have been also proposed [18]. The length of arrester leads can reach several meters, and their effect cannot be always neglected; they can be represented as single-phase lossless distributed-parameter lines or as lumped-parameter inductances.

III. STUDIES

Scoping studies have been carried out on a typical 400kV circuit arrangement (Fig. 1) to examine the impact possible design factors can have on the amplitude of lightning related transients arriving in the GIS substation and the effect that protective measures can have on controlling these overvoltages to acceptable levels. (other voltage levels will be considered in the CIGRE brochure.

The studies examine the influence that different parameters have on the generation of overvoltages within the substation, The impact of travelling waves are investigated at three surge impedance boundaries:

- Overheadline – cable (cable sealing end)
- Cable –GIS connection (cable connector)
- Open GIS disconnector. (20m section of GIS).

The work concentrates on the factors which could be controlled by the utility, these include the cable length, tower footing resistance, earth wires, surge arrester location and cable bonding practice.

- Tower footing resistance (TFR) was considered for values between 10-100Ω to reflect the various terrain which tower constructions may be constructed on.
- Cable lengths between 50-500m are investigated as this will be typical of connections used to link new substations or transformers to existing circuit towers. Most new cables are likely to be XLPE so this is the dielectric considered in the studies.
- The controlling effect of surge arresters at the boundaries is examined. Most studies however involve an arrester at the overhead-cable junction.
- The effect of an earth (sky) wire has a key effect on direct strike events and significantly reducing the probability of a back-flashover, so again most of the studies consider a double circuit tower with earth wire.

A couple of scenarios are examined to look at the significance of lightning on sensitivity. The typical lightning parameters for a shielding failure and back flashover (BFO) are described (Table. 2) which consider critical factors like the steepness, amplitude and duration.

- Shielding failure (<14kA)
- Back-flashover (>150kA).

I_m (crest value)	t_f (front time)	S_m (max steepness)	T_h (time to half value)
150 kA	7.1 μ s	42.77 kA / μ s	75 μ s
7 kA	2.55 μ s	16.7 kA / μ s	75 μ s

Table 2. Typical lightning characteristics

Lightning can be modeled using the CIGRE characteristics, which help to define a condition more representative of the concave front slope (Fig. 2) than a straight line. The Heidler lightning model will also perform this function.

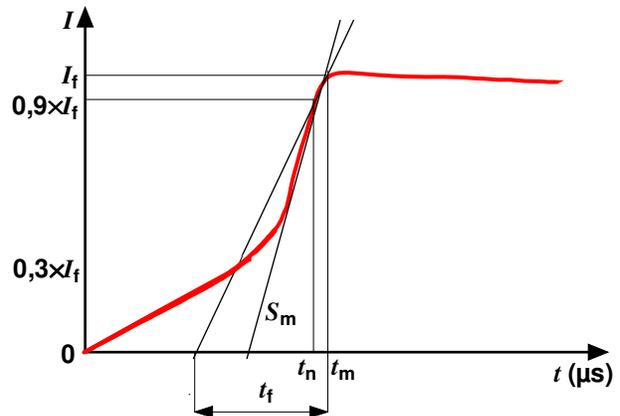


Figure 2. CIGRE concave waveshape [10]

The model considers the cable sheath bonded to the substation grounding grid and to the tower footing at the line end. In reality the sheath is protected by SVL arresters at the line side (typically for a 400kV cable this is 9 kV residual voltage at 10 kA). These arresters operate at the very beginning of any lightning (well before the BFO would appear) essentially bonding the sheath with the tower earth.

The representation of the grounding impedance at the landing tower can also influence the results. This can be a common grounding for the sky wires, the surge arresters and the cables screens. In general, it will be represented as a constant low-value resistance (e.g. less than 5Ω).

Although this work concentrates on short cables there has been some work within CIGRE, looking at long insulated cables, particularly considering the consequence of a lightning stroke impact to an overhead transmission line [19].

IV. OBSERVATIONS

There are many interactions associated with these parametric studies, obviously the magnitude of lightning is a major factor and this will vary between regions. The factors which have a major impact are the effectiveness of the tower footing resistance and the presence of an earth or sky wire.

The back-flashover presents the most onerous condition requiring a surge arrester at the overhead-line & cable boundary, which subsequently controls most of the remaining conditions for low values of TFR ($<20\Omega$).

The connection of the cable sheaths to the grounding electrode of the first tower can result in a significant part of the lightning current, which is circulating in the tower, being transmitted in to the sheaths and the grounding conductor. If there are sensitive rise of earth potential issues this may need to be carefully examined.

One of the original drivers behind this work was the effect of cable length on voltages seen within the substation. The effect of a BFO in the last span (see Fig. 1) at the cable-GIS connection and the open disconnector reference point is illustrated in Fig. 3. This considers a 20Ω tower footing resistance, the 10Ω TFR does not cause a flashover condition. As the TFR increases, the voltages seen at these interfaces also rises (Fig. 4).

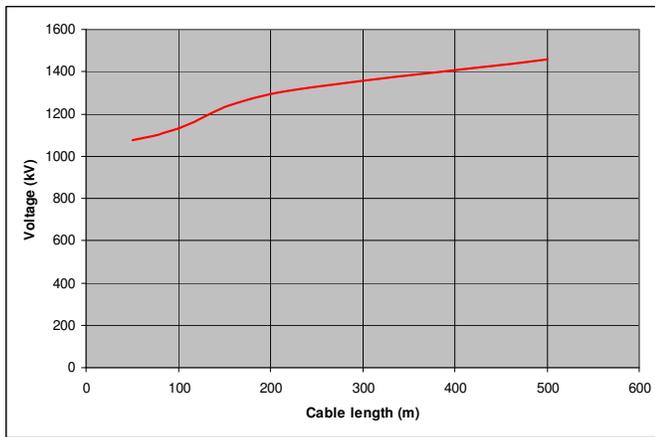


Figure 3. Variation of voltage in GIS with cable length (20Ω TFR, BFO on second tower)

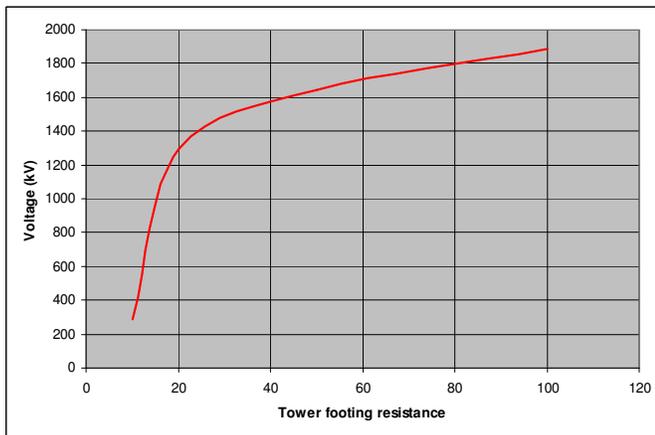


Figure 4. Variation of voltage in GIS with tower footing resistance (200m cable, BFO on second tower)

The impact of modelling variations of the back-flashover condition can be quite dramatic on study results, mainly due to the high frequency effect on any circuit inductance. Simplistic models will provide very conservative results, possibly resulting in the specification of more surge protection than is

necessary. This can become expensive if GIS surge arresters or significant improvements to tower footing resistance is identified. Consequently more sophisticated models for the back-flashover help to provide a more realistic evaluation.

The probability of an event is a major consideration when looking at the degree of mitigation a utility is prepared to install in order to prevent a flashover. The likelihood of a lightning strike at the last tower is very low. Having a BFO at the last tower is even lower because the cables make the footing resistance of the last tower even lower and the arresters prevent the BFO for majority of lightning there.

It could be argued this has been seen in operation, since the mean time between failure (MTBF) value for a 420 kV GIS is of the order 55 years [1] for all types of dielectric breakdown. Approximately 5% could be lightning related suggesting a very low failure rate (in excess of 1000 years). Utilities have so far reported positive experience with arresters at the line side only, although these have only been operational for 10-20 years [26]. The impact of age on GIS is more likely to degrade the seals and leak SF₆, which may degrade dielectric strength, however topping up should ensure the dielectric strength remains, unlike solid dielectric. At this stage, though we do not know what percentage of these GIS substations have cabled line entries.

V. RECOMMENDATIONS

There are two points to consider on the subject of insulation coordination, firstly removing the likely cause of over-voltages such as the lightning, the back-flashover or large surge transition boundaries. Secondly, the strategic use of protective measures such as surge arresters. The extent to which this can be achieved is down to economics, since the solution has to be cost effective.

Shield wires and improving the tower footing impedance will have a major influence on preventing lightning strikes and back-flashovers. Improvements to get below 10Ω will be worth concentrating on.

Installing a surge arrester at the line cable transitions will protect against all but the most aggressive back-flashovers. These are very low probability events and compared to other likely forms of dielectric failure may be difficult to economically justify. If the network is solidly grounded, surge arresters with a lower residual voltage and protective level may be considered, however the higher energy handling capability and exposure to temporary over-voltages must be evaluated.

Transmission line arresters on the last couple of towers or running arrangements which avoid high surge impedance transitions (low to high), such as transformer feeder circuits are worth considering. Where this cannot be avoided surge arresters will probably be required within the GIS.

VI. CONCLUSIONS

This work started out in an attempt to simplify some of the

advice regarding over-voltage protection for GIS or transformers connected to overhead-lines by short cables sections. However, insulation coordination can become much more complex when equipment of different surge impedances are connected in series. This is particularly relevant where short cables are used to connect overhead lines into GIS or transformers. The presence of the cable can increase the voltage seen at the remote end, thereby increasing the likelihood of flashover. The choice of protective equipment may be limited, so a design compromise may be necessary. This paper highlights some of the techniques to lower the risk of equipment flashover.

Studies, so far, indicate that the use of a surge arrester at the line cable junction and reducing the TFR of the last few towers to 10Ω or below will significantly lower the risk of a flashover within the GIS. If the TFR cannot be physically lowered to these suggested levels then surge arresters within the GIS may be required to control the voltage to a value below the equipment impulse level.

The CIGRE brochure will provide a much more expansive review of the sensitivities and options when the work is completed.

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VIII. BIOGRAPHIES

Alain Xémard was born in France on December 20, 1961. He graduated from the National Institute of Applied Sciences in Lyon, France, with an engineering degree in electrical engineering in 1985. His research interests include insulation coordination, and development of tools for electromagnetic transient calculation. He has been working at the Research Division of EDF since 1992. He is convener of the CIGRE WG C4 301 dealing with insulation coordination.

Juan A. Martínez was born in Barcelona (Spain). He is Profesor Titular at the Departament d'Enginyeria Elèctrica de the Universitat Politècnica de Catalunya. His teaching and research interests include Transmission and Distribution, Power System Analysis and EMTP applications.

Mark Osborne was born in South Africa in 1969. He graduated from Lancaster University with a Physics honours degree and completed his doctorate at the University of Sunderland in 1997 in 'Computer based analysis of Custom Power Technology'. He works in the Asset Management section of National Grid UK Transmission. His areas of interest include insulation coordination, substation design and policy development.

László Prikler was born in Mosonmagyaróvár (Hungary) in 1962. He received the M.Sc degree in Electrical Engineering from the Technical University of Budapest in 1986. Since then he is academic staff member of the Department of Electric Power Engineering of the same University. His main teaching and research interest is computer simulation of power system transients.