# Re-appraisal of the Basic Impulse Level (BIL) for 400 kV Underground Cables Using EMTP/ATP

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*Abstract* – **This paper investigates the lightning impulse duty for 400 kV underground power cables using EMTP/ATP and re-assesses the recommended design level based on probabilistic analysis. The work is a part of a larger investigation that will study by computer simulation, the full range of transient overvoltages due to lightning, switching, faults and other temporary overvoltages (TOV) on cables within National Grid's transmission system.**

**Keywords:** Transient Analysis, Modelling, Lightning, Insulation Coordination, Surge Arresters, EMTP.

## I. INTRODUCTION

Power cables for use at 400 kV are designed according to the required transient impulse and power frequency voltage withstand levels. At present both overhead lines and underground cables in the UK 400 kV power system have a basic impulse level (BIL) of 1425 kV. There is a very obvious difference in the risk and magnitude of any lightning impulse in an underground cable compared to that on an overhead line. Reducing the BIL for underground cables would potentially reduce the capital cost of new oil-filled cable systems. Cables could be smaller and installed with longer section lengths which should have economic advantages.

This investigation is of the inherent response of the overhead line (OHL), cable and power system due to lightning phenomena and not of the overvoltage protection, rod-gap design etc. National Grid's transmission system is quite extensive, highly interconnected and has very high fault levels. For all practical purposes it can be regarded as an infinite system. So, in the test network, reflections from the far end have been carefully eliminated by appropriate and proper modelling to get only the inherent response in terms of overvoltages for this BIL review. Only successive reflections between the lightning position and the cable sealing end were considered for the final peak overvoltage and for slower wavefronts.

## II. OVERVOLTAGES & BIL

The BIL specification measures the ability of equipment to withstand representative overvoltages. The BIL is specified with reference to a specific waveform: 1.2 μs rise time, 50 μs time to decay to half value. This is commonly referred to as a lightning impulse wave.

Lightning can impinge on an overhead line via: a direct strike to a phase conductor (shielding failure); or a strike to the overhead line shield wire, which then flashes over to the phase conductor (backflashover). The polarity of a lightning stroke can be positive or negative, and is further classified as either a first stroke or subsequent stroke. Probability curves for different forms of lightning strike have been published. Ref [1] details such probability curves as those shown in Fig.1.

In this paper, as in [2] a negative polarity lightning stroke was considered since more than 90% of the total number of flashes to ground are of negative polarity [3-4]. Regarding the current magnitude to be used in lightning studies, [5] states that lightning strokes of amplitudes less than 20 kA, can bypass the overhead shield wires and strike directly on the phase conductors. Whereas, amplitudes, in the range of 20 kA up to values rarely exceeding 200 kA, cause backflashovers. Using the electrogeometric model [6-7], the maximum shielding failure current, for a typical overhead line, was calculated to be approximately 17 kA. However, the effectiveness of the shield wire may be compromised in exceptional geographic locations, hence the phase conductor could experience higher lightning currents. In addition to a maximum 20 kA shielding failure event a more extreme current injection of 35 kA was also considered, to see the effect of lightning on poorly shielded OHLs. In order to simulate these lightning events, a typical overhead line and cable with other power system plant was modelled and connected so that the propagation of lightning transients could be simulated. The voltage observed at the cable sealing end (CSE) is the parameter of concern in these studies. A large number of studies have been performed, to check all aspects including voltage sensitivity to changes in system parameters.

## III. SIMULATION & MODELLING METHODOLOGY

EMTP/ATP [8] has been used for the simulation. The mathematical model used to represent the underground

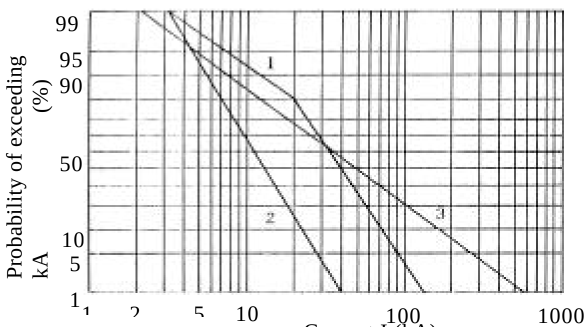



**Fig. 1 Distribution Functions of the Peak Values of (1) Negative First Strikes; (2) Subsequent Strikes; (3) Positive Strikes.**

cables and overhead lines was the constant parameters travelling wave model. This model has been used because it is simple and easy to use. Also, the results are slightly pessimistic and so ideal for planning criteria. All modal parameters were calculated at one fixed (dominant) frequency [8-9]. Live and LV system tests done in the past within National Grid show that the results obtained using the constant parameters travelling wave model compare quite well with the measured results [10].

**A. Lightning**

A current impulse source was used to represent the lightning stroke to one of the overhead line conductors. The current injected was defined by the following double exponential expression:

$$f(t) = I\left(e^{\alpha t} - e^{\beta t}\right) \quad (1)$$

The values of I, $\alpha$ and $\beta$ were defined so that a 1.2/50 μs waveform as defined in [11] was observed at the point of current injection. For a 1 $A_p$ lightning current with t in s:

I = 1.0373, $\alpha$ = -1.46591E+4, $\beta$ = -2.4689E+6

For shielding failure studies current magnitudes of 7.09 kA, 20 kA and 35 kA were injected onto a phase conductor. The peak current of 7.09 kA gives rise to a voltage surge, with a peak value of 1425 kV (BIL for a 400 kV system) on the overhead line. For backflashover studies, currents of 100 kA and 150 kA were injected onto the earth wire (shield wire) of the overhead line system at a tower position, hence simulating a lightning strike to the top of a tower. The backflashover was simulated with a voltage controlled switch. The struck earth wire and an overhead line phase conductor were connected when the voltage between them exceeds 1600 kV ($U_{50}$ for National Grid's arcing horn for 1.2/50 μs).

**B. Overhead Line**

Overhead lines were modelled as a 7 conductor system, (6 phase conductors and 1 earth wire). The overhead line earth wire was grounded at the end of each section of overhead line, via a tower footing resistance. For shielding failure studies the overhead line was modelled as two sections, 10 km and 1 km. For backflashover studies, tower modelling is rather important, so towers were placed 333 m apart and each tower was represented by a travelling wave model with a surge impedance of 90 Ω and a propagation time of 0.14 μs [6] between the tower top and the tower footing resistance.

**C. Underground Cable**

A length of 7.2 km cross-bonded cable was modelled comprising of 18 minor sections. At every joint the cable cores were transposed and the cable sheaths were connected straight through. The length of each minor section of cable was chosen to be 400 m and was modelled as a 6 conductor system, (3 core conductors and 3 sheath conductors).

Bonding leads were used to connect cable sheaths at section joints. Two methods were used to model bonding leads to check sensitivity:

– A travelling wave bonding lead model
– A lumped parameter bonding lead model

The travelling wave bonding lead model was calculated in the same way as an underground cable, i.e. using the constant parameters travelling wave model. In the lumped parameter bonding lead model, leads were modelled as an equivalent comprising of an inductance in series with a resistance and a capacitance to ground.

Cable sheaths were grounded, using bonding leads, at every third minor section (1 major section = 3 minor sections), and at both sealing ends. The grounding resistances used at these cable locations were referred to as earth resistances. These earth resistances were assumed to remain constant with varying calculation frequency. Earth resistivity, which is different to a lumped earth resistance, was set to 20 Ω.m.

**D. Non-linear Devices**

Non-linear devices such as sheath voltage limiters (SVLs) and surge arresters (SAs) were modelled using their V-I characteristics.

The purpose of the SVLs is to limit the voltage on the cable sheaths and the sectionalising barriers. These devices have some effect on core voltages due to mutual coupling. To check this, a few studies were performed to look at the effect of SVLs on cable core voltages. However, the majority of studies performed used a cable system that did not incorporate SVLs. A cable system that does not incorporate SVLs would give higher voltages than a system with SVLs. Additionally, incorporating too many SVLs in the system caused iteration problems in EMTP/ATP.

Surge arresters were included in some studies when injected current was 20 kA or above, to see the effect of surge arresters on voltages. The surge arrester characteristics used were based on a lowest rated voltage which would be acceptable on National Grid's 400 kV system.

**E. Overhead Line Arcing Horns**

Overhead line arcing horns were used in the 35 kA shielding failure studies. Arcing horns were placed 500 m from the CSE, and modelled as time-controlled switches connected between the overhead line and ground. Arcing horn flashover can be unpredictable as it is not solely voltage dependent. Time delays due to ionisation and environmental conditions may exist. To model extreme system conditions flashover times before and after the surge peak were chosen.

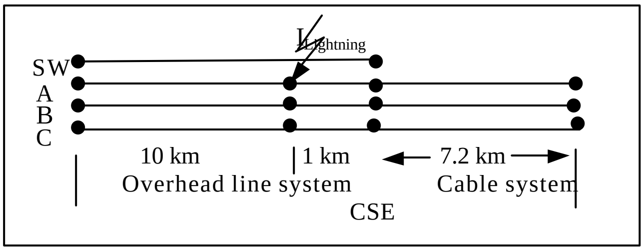
**F. Load**

To study the worst case scenario, no load was connected at the receiving end of the cable. However, the effect of the load would only become apparent when the surge was reflected from the cable-load node. Since no reflection from the open-circuited end of the cable was wanted, it did not matter if a load was connected at the end of the cable or not.

## IV. TRANSIENT STUDIES PERFORMED

To simulate the overvoltages generated at the CSE and within the cable system, the cable was connected to the end of an overhead line which was subjected to a direct lightning stroke (shielding failure) or a backflashover. Fig. 2 shows the system diagram used for shielding failure studies.

The overhead line was 11 km long, the line was divided into two lengths, one 10 km and the other 1 km. This was done so that lightning current can be injected 1 km from the CSE. The cable has 18 minor sections, each 400 m in length, this gives a total cable length of 7.2 km. The British cross-bonding arrangement was applied to the cable, i.e., the cores



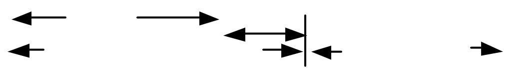


**Fig. 2 Shielding Failure System Diagram**

were transposed and the sheaths were connected straight through. The connections between cable section sheaths were made with lumped parameter bonding lead models. No SVLs were incorporated in the cable construction for the base case. Table 1 summarises the studies performed.

In the majority of studies, the test system was not connected to a system power supply (i.e., a dead system) and so the results are incremental transient voltages and currents that can superimpose at any point on the 50 Hz wave at the time when lightning would struck. Effectively, these studies are the result of a lightning strike at the point of zero voltage on the 50 Hz wave. Normally these transients can be added algebraically, but when surge arresters or rod-gaps are present the physics is quite complex and the overall results would be significantly different. So additional studies were performed when a source was added in the system (live system) to verify the results and to obtain actual system voltages with surge arresters.

### A. Shielding Failure Studies

i) Simplified System

The objective was to establish what governs the overvoltages in a complex multi-conductor cable system. A simple one conductor overhead line and one conductor cable was taken and gradually the model was made more complex, by taking account of 3-phase coupling, grounding, grounding resistances etc. As the model became more complex the amount of current injection had to be altered such that the peak voltage at the point of injection remained at a constant value of 1425 kV.

ii) 7 kA Current Injection Studies

*Current Magnitude Calibration Study*

The cable was replaced by an identical overhead line to determine the current source magnitude to achieve 1425 kV at the point of current injection on the overhead line, and at the CSE. This current injection was approximately 7 kA.

*Base Case Studies*

The voltage at the CSE was investigated for a system with base case parameters. The difference between the lumped parameter and the travelling wave bonding lead models was also investigated.

*Sensitivity Studies*

The following base case parameters were changed in order to determine the sensitivity of voltages to changes in system parameters:

– Inclusion of SVLs in cable construction
– Number of cable sections
– Bonding lead length
– Earthing resistance at the CSE
– Tower footing resistance
– Number of overhead line towers
– Line and cable constants calculation frequency

**Table. 1 Summary of Studies Performed**

| | |
|---|---|
| **DEAD SYSTEM** | |
| **Shielding Failure Studies** | |
| i) | Development of 1 conductor to complex system model |
| ii) | 7 kA current injection studies, 1 km from CSE<br>- Current magnitude study<br>- Base case studies<br>- Sensitivity studies |
| iii) | 20 kA and 35 kA current injection studies, 1 km from CSE<br>- 20 kA base case study with and without surge arresters<br>- 35 kA, without arcing horn flashover, with and without surge arresters<br>- 35 kA, with arcing horn flashover at front and tail of wave, with and without surge arresters |
| iv) | 35 kA current injection study at CSE |
| **Backflashover Studies** | |
| v) | 100 kA and 150 kA current injection studies, 1km from CSE, with and without surge arresters. |
| vi) | 100 kA and 150 kA current injection studies at CSE, with surge arresters |
| **LIVE SYSTEM – 50 Hz 420 kV (1.05 pu) source** | |
| vii) | 35 kA shielding failure current injection studies, 1 km from CSE, with and without surge arresters |

iii) 20 kA and 35 kA Current Injection Studies

In addition to assessing the voltages observed at the CSE, the 20 kA and 35 kA current injection studies investigated the effect of arcing horns and surge arresters on system performance.

### B. Backflashover Studies

For these studies, some changes were made to the overhead line tower model (see section III.B "overhead line"). A current of 100 kA and 150 kA was applied to the top of a tower 1 km away from the CSE.

### C. Live & Dead System Comparison

A 50 Hz, 420 kV (1.05 pu) voltage source behind a system reactance was applied to the end of the overhead line. Two 35 kA shielding failure tests were repeated to determine the effect of the live system.

## V. RESULTS & DISCUSSION

Simulations were run for a total time of 70 μs. The reflection from the far end of the overhead line arrived at the CSE at approximately 70 μs (over 90 μs for the cable) and hence the study was rendered invalid after 70 μs. Discussions are based upon the peak voltage recorded in the first 5 μs, as this value relates directly to the BIL criteria. The final highest peak voltage, over the time interval 5-50 μs, is also recorded. Table 2 shows a selection of results from the studies performed.

### A. Shielding Failure Studies

i) Simplified System Studies

With a one-conductor system the voltage at the CSE was approximately 235 kV. As the system became more complex with the addition of more conductors and a grounding system, the voltage at the CSE fell significantly to between 118 kV and 137 kV (for an injected current of 7 kA), depending upon the value of sheath grounding

**Table. 2 CSE Transient Voltages - Selection of Study Results**

| Ref No. | Study Description, Key: | CSE Voltage and Time to Peak ($kV_p$ (μs)) |
|---|---|---|

| | cond.-conductor BLs-bonding leads w/o-without f/o-flashover | First peak 0-5 µs | Final peak 5-50 µs |
|---|---|---|---|
| DEAD SYSTEM (For Incremental Transient Voltages) | | | |
| Shielding failure, 1 km from CSE | | | |
| | Simplified System | | |
| 1-1 | 1 conductor system | 235 (2.1) | - |
| 1-9 | 7/6 cond. with earth pts. | | |
| | 5 Ω - earth resistance | 137 (2.2) | - |
| | 0.1 Ω - earth resistance | 118 (2.2) | - |
| | Base Case + | | |
| 1-11 | 7 kA inj (lumped BLs) | 180 (1.1) | 204 (20.4) |
| 1-32 | 20 kA w/o SAs at CSE | 509 (1.1) | 576 (20.4) |
| | 35 kA, no arc. horn f/o | | |
| 1-33 | w/o SAs at CSE | 890 (1.1) | 1008 (20.4) |
| 1-35 | with SAs at CSE | 762 (1.1) | 788 (20.2) |
| Backflashover, 1 km from CSE | | | |
| 1-41 | 100 kA, w/o SAs at CSE | 228 (0.4) | 586 (49.6) |
| 1-43 | 150 kA, w/o SAs at CSE | 357 (0.3) | 871 (49.6) |
| 1-44 | 150 kA, SAs at CSE | 357 (0.3) | 759 (49.6) |
| LIVE SYSTEM (For Actual CSE Voltages) | | | |
| | 35 kA, no arc. horn f/o | | |
| 1-47 | w/o SAs at CSE | 1239 (1.1) | 1357 (20.4) |
| 1-48 | with SAs at CSE | 848 (1.2) | 854 (19.1) |

resistance at the CSE. This showed the importance of representing all the components in detail as they are in a real system.

ii) 7 kA Current Injection

With the addition of 10 m bonding leads, using a lumped parameter model, the voltages observed at the CSE increased to approximately 180 kV. This shows the importance of representing bonding leads in the cable system. Using a travelling wave bonding lead model, it gave lower but very close values and similar waveforms at the CSE. Hence, for future studies bonding leads were modelled using lumped parameters to get worst conditions. The bonding lead length at the CSE was chosen to be 10 m, usually bonding leads are shorter than 10 m. Using 5 m bonding leads gave a voltage of 143 kV at the CSE, this highlights the dependence of voltage upon the bonding lead length at the CSE.

The addition of SVLs on results was investigated. It was found that SVLs reduced the final peak voltages between 5 µs and 50 µs to some extent, but the first peak was unaffected. Again, to get the worst conditions, SVLs were not included in further studies.

Changing the earth resistance at the CSE from 0.1 Ω to 20 Ω resulted in a voltage increase at the CSE of approximately 4 kV (<3%) first peak, and final peak by about 30 kV (15%). Changing the number of towers modelled, the tower footing resistance and the cable/line constants calculation frequency had negligible effect on the results at the CSE.

iii) 20 and 35 kA Current Injection Studies

A 20 kA current injection resulted in a peak voltage of 509 kV at the CSE. The use of surge arresters had no effect on the voltages observed.

With 35 kA, the peak voltage at the CSE reaches 890 kV at the first peak and 1008 kV at a later time of approximately 20 µs. The use of surge arresters on each phase at the CSE reduced the voltages observed to 762 kV and 788 kV respectively. In the event of an arcing horn flashover surge arrester duty is less.

With a 35 kA current injection directly at the CSE, with surge arresters located at this point, the voltages reached 771 kV (first peak) and 783 kV (final peak), shows the presence of the surge arresters was a dominant feature.

**B. Backflashover Studies**

With backflashovers, the first peak voltage at the CSE was dependent on the voltage difference between the overhead line earth wire and the phase conductor at the instant of backflashover (i.e., the launched wave). The arcing horn was set to flashover at approximately 1600 kV. With the 100 kA source the first peak voltage at the CSE was approximately 228 kV, the final peak about 49 µs later, was much greater about 586 kV. The addition of surge arresters at the CSE did not reduce these voltages.

When considering a 150 kA current source the first peak voltage was 357 kV, surge arresters did not reduce this peak, however, surge arresters did reduce the final peak from 871 kV to 759 kV.

Backflashovers directly at the CSE gave first peak voltage of 885 kV and 977 kV for 100 kA and 150 kA current injections respectively.

**C. Live & Dead System Comparison**

All the studies so far reported have been performed on a de-energised (dead) system and the resulting transients were incremental voltages. The 35 kA current injection study (study 1-33 in Table 2), the most onerous shielding failure study, was taken to check the actual voltages when a 420 kV (1.05 pu) source was connected to make it a live system.

Without surge arresters at the CSE, the voltages for the first and final peaks differed from the previous study results by approximately 349 kV (see Fig. 3 and 4). The expected voltage difference should be 343 kV though, this value was increased slightly due to the coupling of the overhead line conductor system. When surge arresters were added to the system at the CSE, the voltages observed were 848 kV and 854 kV, first and final voltage peak values respectively. Note that the surge arresters experienced higher currents due to the larger CSE voltages, hence the energy dissipation was also larger, as shown in Fig. 5 and 6.

**D. Summary of Results**

i) Incremental Voltages (Dead System)

- 7 kA shielding failure studies show that the voltages experienced at the CSE range between 115 kV and 183 kV. The current 7 kA results in a 1425 kV voltage surge on the overhead line.
- For a 20 kA current injection, the voltages observed at the CSE were approximately 509 kV.
- A 35kA current injection gave a voltage at the CSE of 762 kV with surge arresters at the CSE.
- 100 kA backflashover studies gave a voltage at the CSE of 228 kV (first peak) and 586 kV (final peak).
- A 150 kA backflashover event yielded a voltage peak of 357 kV (first peak) and 871 kV (final peak, or 759 kV if surge arresters were used).

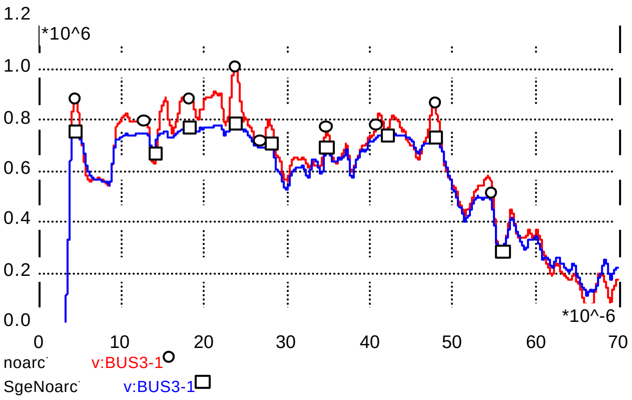



**Fig. 3 Voltages at CSE with and without Surge Arresters (Dead System, studies 1-33, 1-35).**

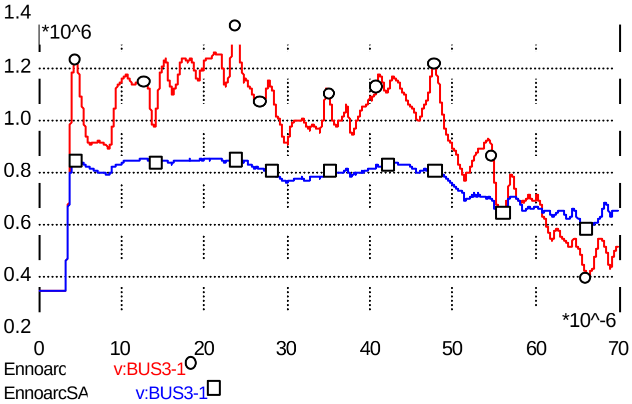



**Fig. 4 Voltages at CSE with and without Surge Arresters (Live System, studies 1-47, 1-48).**

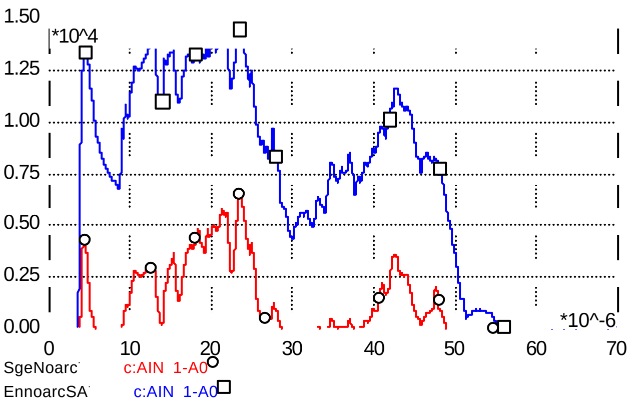



**Fig. 5 Surge Arrester Currents (Live and Dead System, studies 1-35, 1-48).**

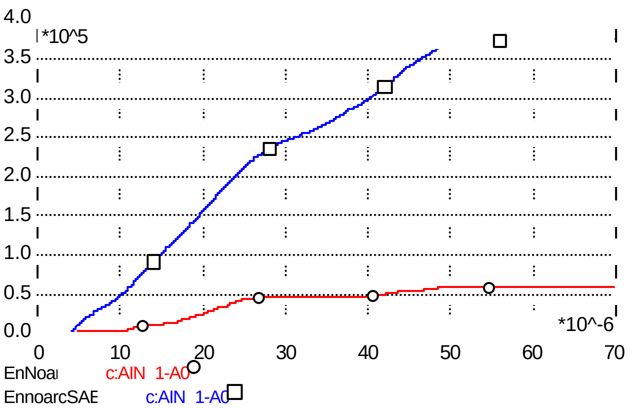



**Fig. 6 Surge Arrester Energy Dissipation (Live and Dead System, studies 1-35, 1-48).**

ii) Actual Voltages (Live System)

– A 35 kA current injection gives voltages of approximately 848 kV with surge arresters at the CSE.

Fig. 7 shows the first and final peak voltage from all studies performed, together with the probabilities of the magnitude of lightning strike occurring. In addition the overall probability of a lightning strike exceeding the current value given is quoted together with the probability of such a lightning stroke hitting a 1 km length of overhead line and CSE in the UK.

## VI. CONCLUSIONS

From the results of comprehensive system transient studies including the most severe lightning simulations, it can be concluded that the incremental transient voltage at the cable sealing end does not exceed 1000 kV. Even considering the live system study results with surge arresters, actual CSE voltage is only 850 kV. All these results are pessimistic as no corona or frequency dependent attenuation was taken into account. From this it appears that for the National Grid 400 kV power system with a BIL of 1425 kV with its normal protection coordination for overvoltages the CSE voltage would always be well below 1000 kV. Therefore, the BIL of 400 kV cable could safely be reduced to 1050 kV, a standard IEC rating.

The results presented in this paper are inherent transient response due to lightning only. It is expected that switching and other system events would not produce such severe overvoltages as lightning. Overvoltages produced by other system situations including open-circuited lines would be protected by standard arrangements such as coordinating gaps and surge arresters.

However, if a lower BIL for cable is to be adopted, then these cables should be protected by surge arresters, mainly because two different plant item having different BIL levels and connected at the same substation, separated by only few metres, should not be protected by coordinating gaps.

There is one other conclusion which can be drawn from these studies, relating to the insulation coordination design of sheath system in cables. Sheath/ground and sheath barrier voltages at a cable joint are produced directly by the incremental transient voltages in the cable conductors. Unlike the main cable insulation which must never fail in the life time of a cable, sheath barrier and sheath/ground insulation is not so critical.

At present cable sheath design is based on a full BIL (1425 kV, 1.2/50 μs) application at the CSE. These studies show that it is never possible to have 1425 kV at the CSE, but between 850-900 kV. Thorough examination of Fig. 7 would reveal that for sheath system design a more realistic value is about 500 kV (or preferably a 20 kA lightning current injection) at the CSE which takes account of 85% of all lightning. This gives an overall probability of no more than about one or two incident in the life time of the cable when the first few joint barriers may see a voltage approaching or exceeding its design limit. This may be the most cost effective way of designing the sheath system, as

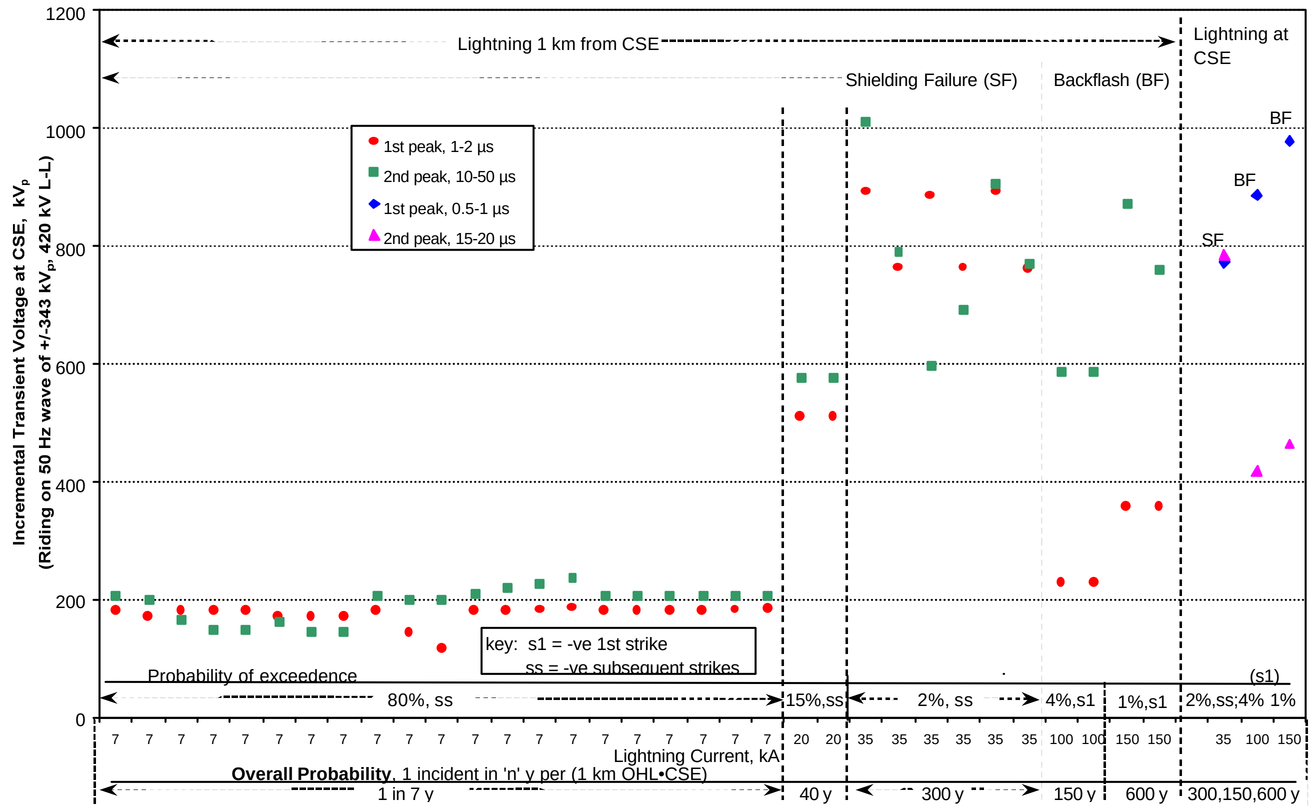



**Fig. 7 Peak Voltages at Cable Sealing Ends due to Lightning – Summary of Results**

impulse testing on an actual cable joint at National Grid's HV laboratory showed that the barrier can take 170% of the design figure without failure.

## VII. ACKNOWLEDGEMENTS

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