# The IEEE Flash Program : A Structure for Evaluation of Transmission Lightning Performance

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## 1. INTRODUCTION

The IEEE FLASH program has been used since the mid 1980s for study and calculation of transmission line lightning outage rates. It was originally written as an adaptation of Anderson's contribution [1]. Since its adoption by the IEEE in 1985 [2], every aspect of the program has received scrutiny. Some issues were addressed in revisions of the method in 1993 [3] and 1997 [4]. However, the fundamental simplification, in the direct calculation of lightning overvoltage, using a fixed equivalent front time, continues to provide reasonable and accurate estimates of stroke currents and line outage rates. This summary reviews the FLASH program and uses its structure to point to criticisms, supplemental models and extensions.

## 2. LIGHTNING INCIDENCE TO GROUND

The FLASH program is old enough to rely on estimates of Ground Flash Density (GFD) *Ng* based either on Thunderstorm-Day (TD) or Thunderstorm-Hour (TH) data. Anderson's equation [5] for *TD* and MacGorman's results [6] for *TH* are recommended.

$$Ng = 0.04\ TD^{1.25} \qquad (1)$$
$$Ng = 0.054\ TH^{1.1} \qquad (2)$$

Inter-comparisons of Lightning Flash Counter (LFC) and TD data in many countries suggest a factor-of-two dispersion around Anderson's result. There is a similar discrepancy between LFC and TH data between American results [6] and results for Canada [7]. Statistical analysis of the Canadian work suggested that the square root of the normalized long-term annual ground flash density, taken from 74 sites, was normally distributed with a standard deviation of 0.23. Thus, at a 95% certainty level, the maximum annual flash density should be twice the long-term average value.

GFD measurements, obtained from at least 400 records using a suitably calibrated instrument, can be entered into the FLASH program by entering a value of $TD = (25\ Ng)^{0.8}$, where the flash density is in flashes per square kilometer per year. Both CIGRE 10 kHz LFC [8] and lightning location networks eg [9] are suitable instruments. While LFC and lightning location networks do not always respond to the same lightning, their estimates of GFD are in satisfactory agreement.

Optical transient detection (OTD), based on a NASA satellite launched in 1995 [10], can be used to provide low-cost estimates of ground flash density throughout the world. The instrument is relatively free of local detection bias, although it samples more at the poles and less at the equator. OTD observations having at least 400 counts per pixel (typically only the mission summary data) tend to match ground-based measurement contours in many areas of the world, notably Canada, USA, South Africa, Columbia, Jamaica but not Brazil.

A conversion factor from OTD to GFD is suggested. The sampling rate at the equator (0.1%), pixel size (typically 37 x 37 km) and an estimated Optical (Cloud, Ground, Leader) to Ground Flash ratio OT/GF =10 give an overall relation of 400 OTD per year in a 37x37 km pixel = 8 Flashes per $km^2$ per year.

Figure 2 shows the mission summary data of the OTD equipment for Japan. Based on the relation given above, the east of Japan has a peak OTD of 200 counts in five years, corresponding to a ground flash density of 0.8 strokes per $km^2$ per year. The minimum value, seen through most of the country, is OTD=100 in five years, or GFD = 0.4/$km^2$-year.

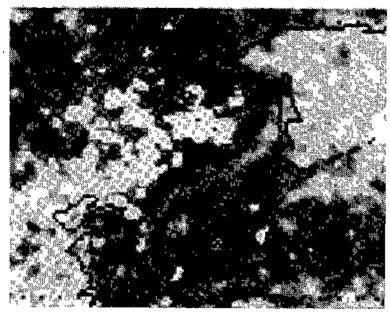

Figure 1: NASA Optical Transient Density Observations Mission Summary for Japan, April 1995 – December 1999

Boccipio [11] suggests that the ratio OT/GF varies from >10:1 to <1:1 across the continental USA. This high variation, combined with the high ratio of OT:GF, may reduce confidence in the use of OTD data as a substitute for long-term thunder observations. Also, Based both on video recordings and on high-resolution measurements of lightning locations, many lightning flashes are seen to have more than one simultaneous ground termination.

## 3. LIGHTNING INCIDENCE TO OVERHEAD LINES

With a value for ground flash density, the FLASH program determines the number of strokes that terminate on the transmission line, using a mix of several different analyses. Each element provides 'the best description' but none of them is consistent for all calculations. The number of strokes to the line $Ns$ is based on Eriksson's expression:

$$Ns = Ng\,(28\,h_t^{0.6} + b)\,/\,10 \qquad (3)$$

using $h_t$, the shield wire height at the tower top. The shielding calculation in FLASH uses the average shield wire and phase conductor heights, based on both tower heights and sags. While both electrogeometric and leader-inception models suggest that taller structures should receive higher median currents, the advice of Anderson and Eriksson [12] (no observed variation up to 60 m) is still taken.

For the shielding calculation, a current–dependent striking distance from Whitehead's research is used. While Whitehead and Mousa formulate the shielding problem using an increased striking distance to tower or line, Anderson chose to reduce the striking distance to ground instead. Rizk [13] placed Anderson's analysis on a much firmer theoretical foundation and, for this reason, the FLASH program continues to use a height-dependent reduction in the striking distance to ground.

The variation in advice regarding perfect shielding effectiveness is perhaps the widest in the topic of transmission lightning protection. Eriksson's model suggests that complete line shielding can be achieved without overhead groundwires (OHGW), using only the towers and short spans. The electrogeometric models suggest that OHGW negative shielding angles will be needed as line heights increase from 30 m to 70 m. Hileman's observation [4,14] is that most discrepancies among models disappear when a small non-zero rate of shielding failures is accepted, leads to convergent advice, including shield angles of +5° for 50-m lines with $Ng$=10.

Shielding models are often extended in scope to include effects of adjacent terrain, three-dimensional slope of ground and non-vertical channel incidence. These refinements have their place. However, fundamental work, using lightning location network confirmation of flashover currents, is also needed to verify the basic assumption in FLASH that 'only small currents sneak under shield wires'.

One active area of interest for the IEEE Working Group, responsible for the FLASH program, is the comparison of lightning location system data with records of transmission line outages using travelling-wave fault recorders. A specific concern can now be resolved from stroke-by-stroke data. Weak first strokes tend to cause shielding failures, and a 'perfect' design will not flash over for these events. However, subsequent strokes, following the same channel, are more likely to cause flashover. There are, on average, two subsequent strokes for each shielding failure. By careful examination of the timing of faults and stroke currents, it is possible to validate existing analysis and to develop better advice for transmission line shielding.

## 4. LIGHTNING PARAMETERS

The first, downward, negative stroke current is assumed in FLASH to be the dominant threat to transmission lightning performance through backflashover. While they have steep rates of current rise, subsequent strokes do not have sufficient amplitude to cause anything but puncture of high-capacitance solid insulation. Large, positive strokes are rare, although the relative incidence of 100-kA positive and negative strokes can be nearly equal, based on some lightning location network studies. Factors working against positive lightning as a threat to transmission lines are the relatively slow rate of current rise, and the increased coupling of OHGW to phase voltage under positive corona, compared to negative. Recently, other lightning parameters have begun to receive additional study. For example, the total charge in the flash describes the energy stress on line surge arresters and Optical Fiber Ground Wires (OPGW).

Anderson's approximation [1] to Anderson and Eriksson's recommended distribution [12,14] agrees at the median and 95% (100 kA) levels for the peak current.

$$P(I_{pk}) = 1\,/\,(I_{pk}\,/\,31\ \text{kA})^{2.6} \qquad (4)$$

There is a high observed correlation coefficient between $t_m$, the 'Minimum Equivalent Front Time' of peak current divided by peak steepness, and peak current $I_{pk}$. A median value of 1.4 μs is given by CIGRE [14] for large currents, along with Equation 5:

$$t_m = 0.154\,I_{pk}^{\,0.624} \qquad (5)$$

With a fixed $t_m$ of 2 μs, the FLASH program co-ordinates with CIGRE at approximately 60 kA, with Equation 5 giving a slow variation up to $t_m$ = 2.7 μs at 100 kA. CIGRE [14] takes great care in modeling the concave features at the front of the lightning wave. Within the IEEE, it is held that these features have little influence on lightning performance, other than by reducing the corona inception and streamer propagation times in the flashover and soil ionization processes.

With the recent interest in values of charge, it is timely to introduce J.G. Anderson's approximations to the distributions of total transferred charges given by Berger et al. [15]:

$$P\,(\text{total negative charge}) = 1\,/\,(Q^-\,/\,7\ \text{C})^{1.7} \qquad (6)$$
$$P\,(\text{total positive charge}) = 1\,/\,(Q^+\,/\,85\ \text{C})^{2} \qquad (7)$$

The charge levels $Q^+$, $Q^-$ used in Equations (6) and (7) do not include continuing currents. The probability of charge from Equation (6) is reasonable minimum for line surge arrester specification on unshielded lines and for damage to OPGW.

With the improving success of continent-wide lightning location networks, four digits of precision are reported for the peak stroke currents that have been computed from distance-normalized electric or magnetic field strengths. This implies too much accuracy. Typical variations in receiver gains are on the order of 5-8% after long-term calibration. Both distance and azimuth-related site error corrections need to be derived and applied. Based on Sommerfeld-Norton modeling of the signal propagation, at least one observation point needs to be within 50 km of the lightning to establish undistorted peak signal strength. Tall objects will radiate three times harder than return strokes, so currents to these objects may be over-estimated. Linear scale factors suggest that return stroke velocity is constant, not a random function of stroke current. It would be better to report only one-digit accuracy for stroke current estimates based on radiated fields, with a second digit useful only because most of the errors are likely to be monotonic.

## 5. INSULATOR IMPULSE STRENGTH CALCULATION

The FLASH program re-uses input data regarding tower geometry (OHGW position), along with tower base dimensions, to estimate tower surge impedance. Provision is made for input of a distribution of footing resistance values, since this segmentation is an important aspect of transmission line description in most cases.

An empirical description is used of the electrical impulse strength of insulation, based on older CIGRE work:

$$Strength = (400 + 710\ t^{-0.75})\ \text{kV/m} \qquad (8)$$

The volt-time description can and should be used to calibrate more sophisticated models of flashover strength for non-standard impulse voltages. Motoyama [discussion to 16] carried out one such calibration for the CIGRE leader progression model [14]. A constant streamer time of $t_s$=0.5 μs can also be used.

## 6. CALCULATION OF CRITICAL CURRENT

In the FLASH program, for each of ten values of footing resistance, the current needed to produce a flashover is evaluated at two times. A tower travelling wave model is used at the adjacent-span reflection time. A different, span reflection model is used at a fixed 6 μs. A composite line outage rate is formed from the sum of the rates for each decile of the distribution, using the probability of the lower of the critical currents. The adoption of a ten-point description of footing resistance distribution did more to improve the predictions of the FLASH program, compared to calibration lines, than any other modification.

Surge impedance coupling from driven (OHGW) to undriven (phase) conductors is sensitive in the computation. A voltage-dependent corona-coupling model is incorporated.

## 7. SYSTEMATIC CRITICISM OF FLASH APPROACH

Criticisms of the simplified FLASH model span the entire frequency spectrum, from DC to Radio Frequencies. At the fast transient end, simulation of the effects of 100-ns rise times on structures that are 30 m tall (minimum propagation time also 100 ns) and 300 m apart, should take more care in the following aspects:

- Radiation losses at impedance changes
- Causality of electromagnetic coupling
- Composite modeling (equivalent radius) of tower lattice elements
- Material modeling of galvanized steel members at high current and rate of rise
- Insulation puncture strength at rates of voltage rise that are typically in excess of 2500 kV/μs

Recent work, for example by Ishii and Baba with the computer model NEC-2, addresses some of these issues. However, researchers of high-voltage insulator strength dismiss much of the fast transient effect on transmission line performance. While the estimated and measured overvoltages can be very large in magnitude, they tend to have short duration (100-300 ns typically). These are difficult to generate and study. In addition, present insulator flashover models suggest that the leader will not develop any quicker if narrow-duration overvoltages are applied.

Moving slower in the time domain to the range between 300 ns and 3 μs, several important nonlinear effects become important as the stroke current continues to rise.

- Corona on stricken wires lowers their self surge impedance and also increases the surge impedance coupling coefficient to nearby phase conductors, using a maximum electric field stress of 1500 kV/m to define the corona envelope.
- Streamer and leader development proceeds at high speed when electric stress exceeds 500 kV/m.
- Soil Ionization starts at field strengths above 300 kV/m.

One reason why the FLASH approach works so well is that the evaluation of the stress, at the time of greatest danger to the insulation, incorporates simple but effective models for these factors. The selection of 1500 kV/m for the corona envelope ignores the effects of threshold voltage but represents the dynamic capacitance at high rate of voltage rise tolerably well. At later times, the FLASH corona model is less appropriate. Surge impedance coupling, modified by using the geometric mean of the corona and geometric conductor radius has been shown to match Gary's observations of coupling dependence with voltage for negative polarity [17]. However, one area of weakness in this part of the FLASH model is the poor predictive performance when any of the well-documented models for the reduced footing resistance under high impulse currents are used. This is a function to some extent on the structure of FLASH, which is based on measured values of footing resistance rather than on soil resistivity and geometry. Recent work has suggested that the impulse reduction is not as important as two-layer soil effects in many difficult grounding conditions.

In the time after the adjacent-tower reflection, from 3 to 10 μs, the FLASH program again picks a simplification. Calculation of the number of tower footings connected in parallel at a fixed 6 μs is somewhat coarse and assumes that neither corona nor propagation losses will affect reflections from adjacent towers. Further criticism can be traced back to the use of a volt-time curve for what becomes, after the first reflections from adjacent towers, a nonstandard voltage wave. Also, few evaluations ever flashover at 6 μs if they do not also flashover at the span reflection time. With advanced analysis, for example using EMTP, tail-of-wave flashovers are more often encountered in simulations. In this time range, nonlinear effects in the ground electrodes have dissipated, so the FLASH approximation (low-frequency, low-current resistance) is more easily justified.

FLASH does not analyze the period between 10 μs and 100 μs. In practice, however, Japanese experience with winter lightning shows that many interesting events are still observed. Multi-circuit flashovers, possibly as a result of transient overvoltages resulting from the first tail-of-wave flashover, have been reported from tower observations. Also, positive lightning is ignored in the FLASH model mainly because it is rare in North America, has a lower rate of current rise and a larger improvement in corona coupling coefficient, compared to large negative strokes.

The final area of defects within the FLASH program would be the quasi-static electric-field response of the transmission line structures to the downward leader. Eriksson, Rizk [13], Dellera and Garbagnati [18] and most recently Anderson and King have treated simple cases of structure response (leader inception). Model predictions of the relative speed of downward and upward-connecting leaders can be matched to observation [13]. However, some basic data in this model remain elusive. Evidence from LFC/LLS inter-comparison disputes the assumption that leader charge and stroke current are directly related. The time variation of the relation between electric and magnetic fields for natural lightning can test the hypothesis further.

## 8. EXTENDING THE FLASH PROGRAM

Even with all of its acknowledged limitations, electrical utility engineers and consultants have tried to extend the use of the FLASH program in several ways. Some changes to the FLASH model have been made to make the model more accurate over a wider range of tower heights, with 10-60 m covering typical distribution and transmission lines. The total electrical strength of insulator combinations such as wood and porcelain can be estimated from a geometric sum of the two individual strengths.

So far, the difficult task of describing streamer and leader progression across a wide range of insulator lengths, from 0.1 m to 10 m, has not been achieved with a single model. It would appear that small-gap (0.1-m) flashover is best described only by the streamer propagation time, while the leader propagation time dominates the larger-gap (1-m) flashover and has good experimental support. Adoption of a better insulation model for non-standard lightning impulse waves becomes especially important for distribution systems, which are more affected by induced overvoltages and close spacing of ground electrodes.

The FLASH model has a simple provision to calculate the lightning performance of unshielded transmission lines, using the Eriksson stroke incidence model. However, this analysis does not model the shielding effects of the tower and is mainly a placeholder for future work. Renewed interest in transmission networks without shield wires, taking advantage of HV and EHV line surge arresters, is now increasing in areas with low ground flash density.

## 9. CONCLUDING REMARKS

As first conceived, the FLASH program was intended to provide engineers with a tool to evaluate the lightning performance of existing transmission lines, and to test the effectiveness of such simple modifications as extra insulators or improved grounding. Twenty years later, the program continues to be useful both for teaching and for basic design. Some groups have successfully adapted important elements of the FLASH approach (such as the fixed 2 μs rise time) for evaluation of line surge arresters.

Several of the improved computational models described here have been considered for inclusion in FLASH 2.0. Increasing ease of use and superior detail to some extent favors versions of EMTP [16] although its ability to run multiple cases (for example a segmented distribution of footing resistance) is still limited. On the other hand, the ability to gather relevant geographical data (line plan and profile, resistivity data, individual tower data) into a spreadsheet continues to improve. Perhaps, rather than a recommended EMTP case study, FLASH 2.0 will be a spreadsheet macro, designed to analyze a vector of input data, using the same basic approach as Anderson [1].

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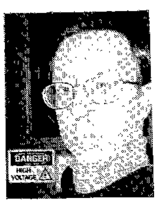

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