An Evaluation Procedure for Lightning Strike Distribution on Transmission Lines

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***Abstract*—For the evaluation of the back flashover risk of a whole transmission line using simulations, probability distributions of lightning strike amplitude and strike density along the line route are needed. In this paper, an evaluation procedure of electric-field based measurement data to calculate the distributions and strike density for each tower of a line is investigated. Experience and recommendations, based on the evaluation of a line route are reported.**

Keywords- Lightning, lightning current distribution

I. INTRODUCTION

The assessment of the lightning performance of a transmission line is a crucial part of its planning process, especially with the growth of transmission networks into more varied terrain due to remote renewable generation. Therefore, where the line route passes through areas of varying lightning activity and challenging soil and grounding conditions with regard to the lightning performance, standard analytical methods to determine the back flashover rate (BFR) and thus the outage rate of the transmission line may lead to unreasonable safety margins and mitigation methods. The determination of the BFR with a transient simulation approach may improve the accuracy of the estimation, but is first and foremost dependent on the probability distribution of lightning strikes along the line route.

In this respect, therefore the application of global or averaged lightning strike data as proposed in [1] may not be suitable for the estimation of BFR, shielding failure and outage rate of the transmission line. Rather actual local lightning strike data, including local lightning strike density and distribution of strike current strength, nowadays often obtained from lightning detection and location systems (LLS), should be applied [2].

Based on the obtained probability distribution strike peak current, the range of strike currents inputted in a multiple run simulation can be defined along the line route, provided that limits for their probability are specified. In the later process of estimating the overall back flashover risk of the transmission line, the total probability of back flashover risk is calculated from the a sum of probabilities of the different strike currents leading to a back flashover at each tower in the simulations and the strike density along the line route.

In general it is the procedure to apply average data from the keraunic level world map or storm duration on a 100 square km basis [1], lightning optical transient density or lightning location systems [3] to derive the lightning strike density and an averaged probability distributions of strike current of first and subsequent negative strikes [1]–[3]. Thereby, the confidence level and standard deviation of a grid square and its size, respectively, is dependent on the number of recorded lightning strike incidents, e.g. IEEE [3] recommends n = 400. However, in some cases the data basis for producing lightning strike density and probability distributions is much smaller, especially in areas with low lightning activity or mountainous terrain with strike hotspots. Up to now there exists no standard or recommendation on how to produce these probability distributions and lightning strike density for a line route from electric field measurements taking local features into account, where the data basis is poor. A first approach is made in [4] for the strike density, which shows the dependency on the strip area along the tower spans, but with a great number of samples available.

In this paper experience and encountered problems in obtaining the lightning strike current and density in a mountainous terrain, where the lightning activity is generally very low are described, and preliminary results and recommendations for an evaluation procedure discussed.

II. LIGHTNING STRIKE DATA SOURCES

Sources for lightning strike data can either be direct current or electric field measurements. Both sources contain their strength and weaknesses. The advantage of direct current measurements with current transformers mounted on the top of towers, such as performed in [5]–[10], is its high measurement accuracy with regard to lightning current amplitude, polarity and strike type. A summary of direct current probability distributions is given in [2]. However the measurement data is limited to one specific location and towers are often located in

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exposed positions to attract lightning to increase the sample size.

On the other hand electric field measurements lack this accuracy due to the electric field to current (E-I) conversion, but cover large areas, at which the accuracy of lightning strike location determination is dependent on the measurement systems set-up, e.g. radio direction finding triangulation depends on the number of measurement stations and their location [11].

For the purpose of increasing the accuracy of the estimation of lightning performance of a transmission line electric field measurement data can be used to determine the strike crest current and strike density probability functions along the line route. The observed time frame of data should include 11 years or one solar cycle [12]. However, with regard to the increase of accuracy all strike incidents available should be used due to the limited number of recorded strikes. Furthermore, the error margin depends on the LLS calibration with respect to first and subsequent strikes. To account for the inaccuracy of the E-I-unit conversion, a safety factor may be multiplied to the resulting current probability density function, e.g. the U.S. National Lightning Detection network features an absolute error of 10 – 20% for negative strikes [2]. In theory these data can then be used for the determination of the strike crest current range applied in the simulations, the final estimation of the back flashover risk of the line, distribution of strike polarity, strike density and strike multiplicity.

In this paper, the lightning detection system from EAtechnology, UK, which is based on radio direction finding techniques, is utilized for this intention. The average location error for a strike up to a distance of 200 km away from the stations is 1 km with 3 kA being the smallest crest current amplitude detectable. [11], [13] At this point in time, strike current amplitude data is only available in ranges of 10 kA. The time period of recorded strikes ranges from 1995 to 2013

III. DEVELOPMENT OF AN EVALUATION PROCEDURE

To develop a procedure to obtain the probability distribution of strike crest currents and strike density along a line route, tower location data from a line is needed. As a starting point for an evaluation the tower locations are taken as the fixed points to query the database and obtain a data set for each tower along the line route. However, some practical problems with regard to the computer-implemented calculation and selection of data have to be dealt with beforehand.

As lightning is random in its nature, flash parameters x must be expressed in probabilistic terms extracted from data measured in the field. Therefore parameters of a flash are described with a log normal distribution with the probability density function

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma x}\, e^{-\frac{1}{2}\left(\frac{ln\left(\frac{x}{M}\right)}{\sigma}\right)^2} \tag{1}$$

There M is the median and σ is the log standard deviation, where median means that 50% of the observations are above a certain value. In computer calculations the median value M has to be calculated from the geometric mean (GM) of n values in formula (2) with a logarithmic sum rather than the n$^{\text{th}}$ root of the sum of values. The log standard deviation is calculated from the geometric standard deviation (GSD) in formula (3) accordingly.[14]

$$GM = M = \left(\prod_{i=1}^{n} x_i\right)^{\frac{1}{n}} = e^{\frac{1}{n}\sum_{i=1}^{n} ln(x_i)} = e^{\mu} \tag{2}$$

$$GSD = e^{\sqrt{\frac{\sum_{i=1}^{n}\left(\ln(x_i)-\ln(GM)\right)^2}{(n-1)}}} = e^{\sqrt{\frac{\sum_{i=1}^{n}\left(\ln(x_i)-\mu\right)^2}{(n-1)}}} = e^{\sigma} \tag{3}$$

The probability that a strike current exceeding a value x then can readily be calculated with the cumulative distribution function of the standard normal distribution in (4).

$$P(X > x) = 1 - \phi(z) \text{ with } z = \frac{ln\left(\frac{X}{M}\right)}{\sigma} \tag{4}$$

With regard to the selection of data, the area around the towers where the database is queried for lightning strike incidents needs to be defined. Furthermore decisions on handling the location errors of the measurement system have to be made. First of all, the size of the area or radius around the tower needs to be chosen with regard to the number of strikes in this area and the level of confidence of the probability distribution. In [4] a strip of 500 m and 2 km is applied, in the standards and technical brochures [1], [3], [15] an electro geometric model (EGM, rolling-sphere model) is recommended, where the radius is dependent on the strike current, thus leading to smaller radii for low strike current amplitudes and smaller sample size. It is obvious that with increasing radius the number of strike incidents increases and thus the level of confidence of the probability distribution. However, as it is the intent to take local topographical effects into account, such as where the line route passes through valleys or along ridgetops, an increase in radius leads to blur effects of these. Therefore the radius is a trade-off between blur effects and level of confidence.

As there exists a limited amount of samples for a given search radius, evaluation criteria for the level of confidence need to be defined. An approach to measure the level of confidence is the application of a simple error analysis, where n is the number of samples from the database, σ the log standard deviation and $\mathrm{SE_n}$ the log standard error in (5), which are all search radius dependent.

$$\mathrm{SE_n} = \frac{\sigma}{\sqrt{n}} \tag{5}$$

The minimum sample size can be deduced from the statistical confidence level of sample mean values $\overline{\mathrm{X}}$ and a deviation of $\frac{1}{2}\sigma_n$ from μ_n, where index n denotes the normal distribution.

$$P\left(|\bar{X} - \mu_n| \le \tfrac{1}{2}\sigma_n\right) = 2\phi\left(\tfrac{1}{2}\sqrt{n}\right) - 1 \tag{6}$$

It follows that with $n = 5$ and $n = 16$, the mean value has a probability of 75% and 95% of deviation only $\pm\frac{1}{2}\sigma$ from μ_n, respectively.

IV. TEST OF PROCEDURE ON A LINE ROUTE

To show all the above mentioned effects we use a 220 km long newly constructed 400 kV line with over 600 towers from the Scottish north coast over the central Highlands to the Lowlands as an example, where high regional and topographical variations are present. Since the strike current amplitudes are at this stage only available in ranges of 10 kA, the decision is made to use always the upper value of each range for a practical evaluation without taking any safety factors into account. For location errors a rigorous approach is taken. The location error is added to the distance between strike location and tower and thus even if the location is in the search radius, the location error places the location outside.

For search radii 1 km, 3 km, 6 km and 12 km around each tower along part of the 400 kV line route from the Scottish north coast to the central Highlands, consisting of 137 towers, the lightning strike database is queried and the geometric mean (GM), equivalent to the median of current amplitude, corresponding log standard deviation σ (SD), the standard error SD_n and the strike density for both positive and negative polarity is determined. As no strikes are recorded within the 1 km radius, the results for 3 km, 6 km and 12 km are presented in Fig. 1, Fig. 2 and Fig. 3 only.

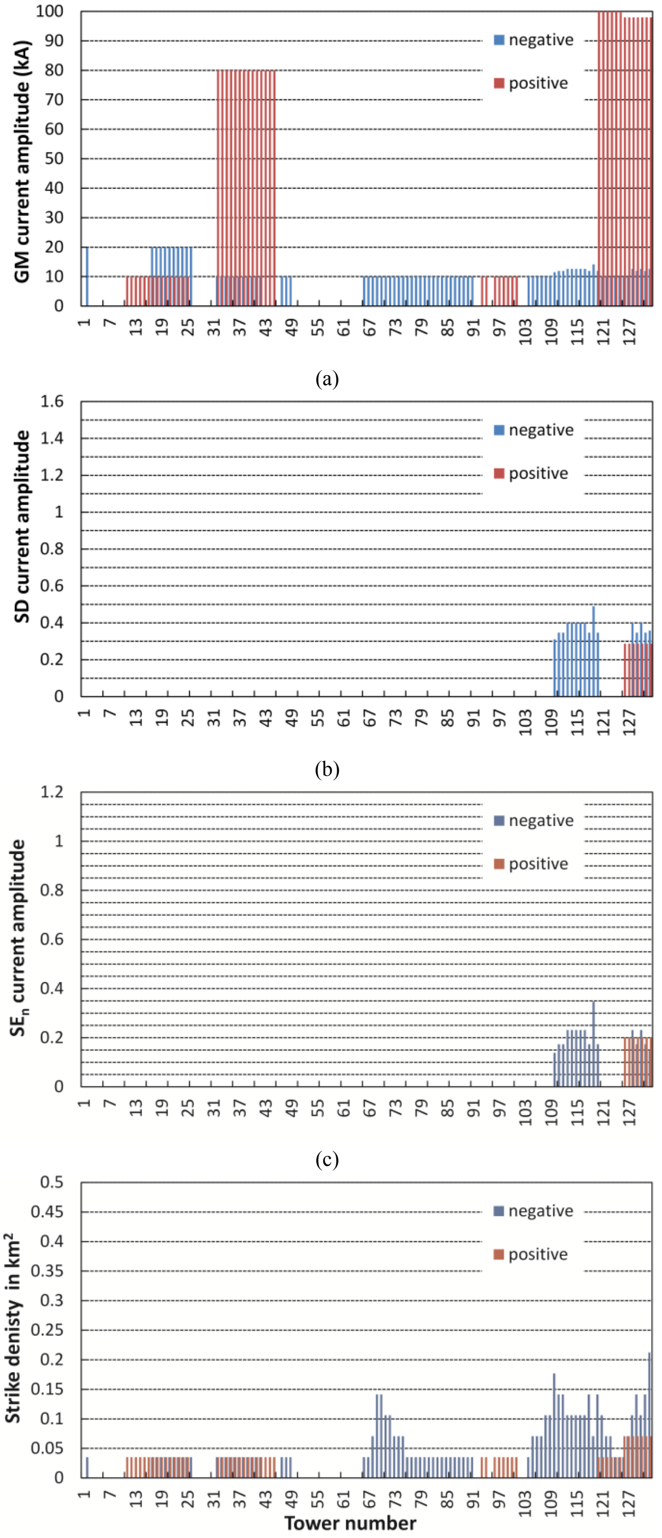
From the results three observations can be made, which can be applied to an evaluation procedure, although the example and produced results are not representable due to the restricted accuracy of current measurements and test on a single line route only. First, there exists the need of a sufficient minimum search radius, see (Fig. 1), as the overall number of samples is small and no standard deviations can be calculated for all strikes within the search radius. This also disables the application of an EGM model. A criterion for the minimum radius can either be standard deviation σ or the standard error SE_n. Although standard deviations of strike currents can be reasonable low for a small sample size (compare Fig. 1 and Fig. 2), such as for positive strikes in the search radius of towers 127 to 137, the sample size is too small to achieve a reasonable level of confidence. Second, when there are enough samples available a further extension of the search radius leads to blurred topographical effects. For example, in a comparison of Fig. 2 and Fig. 3 between tower number 56 and 62, where no positive strikes are recorded for the 6 km search radius, the increase of the radius to 12 km radius leads to the loss of this topographic characteristic. Or between tower number 1 to 25 for negative strikes in Fig. 2, where the increase of search radius leads to an increase of the GM current amplitude, but where the standard deviation is already low for a search radius of 6 km. And third, if not enough samples are available in an extended search radius, it can be concluded that the probability of these strike incidents falls below the 5% significance and can be disregarded. A first proposition may be a maximum radius of approximately 6 km around each tower along the line route, derived from the lightning strike channel length [8], [9].

From a comparison of the strike density in Fig. 2 and Fig. 3, a clear topographical effect can be observed. The strike density in Fig. 2 for a 6 km search radius is significantly higher than for the 12 km search radius from tower 97 to 137, where the line runs over a mountainous area, but also is lower for tower 87 to 97 for negative strikes, where the line runs through a glen. Due to the increased sample size, the concentration of strikes in these areas would either be under- or overestimated. This shows furthermore, that the search radius has to be selected carefully.

For the strike current amplitude distribution and strike density in our case, we employ a minimum number of samples of 5 and a standard error smaller than 0.5 for an evaluation. If there are less than 5 strikes in a 6 km radius, they are declared in the 5% insignificant level. In comparison to the direct current probability distribution in [1] the derived distributions are much smaller in amplitude for negative strikes. For positive strikes the generalization that positive strikes can be neglected cannot be applied, because the strike density for positive strikes is equal to the one for negative strikes at some tower locations.

V. SUMMARY AND CONCLUSION

In this paper, a short discussion of the application of electric field measurements of lightning strikes to include topographical effects in the probability distributions of crest currents is presented. Furthermore an investigation into the development of an evaluation procedure of lightning strike data is presented, which shows that the determination of the search radius for lightning strike incidents around a tower location is difficult and dependent on the number of samples and their distribution. However, to increase the accuracy of probability distributions by including topographical effects as far as the lightning strike database permits, an adaptable search radius combined with a limit for the standard deviation or standard error can be employed conditional on a minimum number of samples. The distinct difference of GM of the lightning strike crest current and percentage of positive strikes in our case and the numbers proposed by CIGRE [1], further shows that the proposition in [2] to use local data as far as possible should be followed. Furthermore topographical effects, such as line routes following ridgetops or passing through glens, can lead to different strike densities and should be included in an evaluation.



(a)

(b)

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Fig. 1. Evaluation of strike probability distributions along a 400 kV line route from the Scottish north coast to central Highlands, lightning strike search radius 3 km around each tower

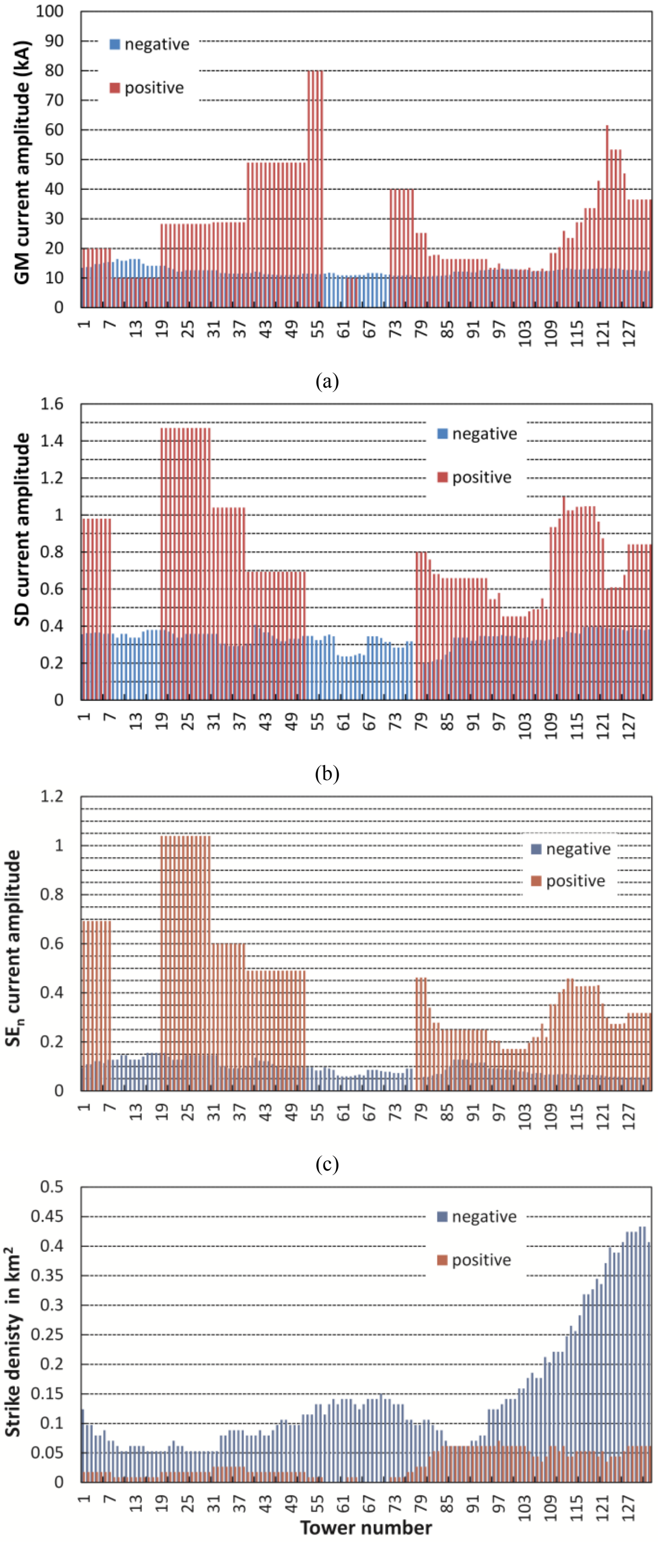

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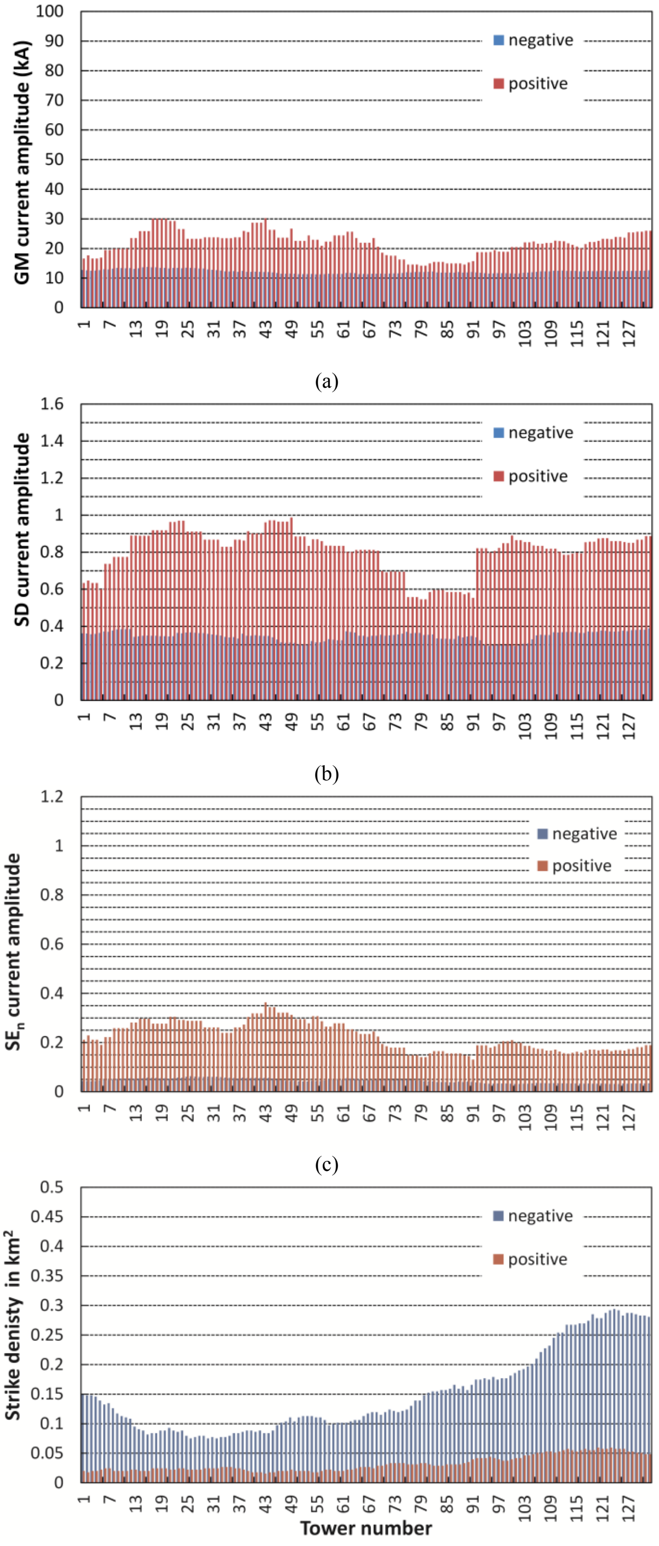
Fig. 2. Evaluation of strike probability distributions along a 400 kV line route from the Scottish north coast to central Highlands, lightning strike search radius 6 km around each tower



(a)

(b)

(c)

(d)

Fig. 3. Evaluation of strike probability distributions along a 400 kV line route from the Scottish north coast to central Highlands, lightning strike search radius 12 km around each tower

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