Monte Carlo Simulation of Lightning Strikes to the Nelson River HVDC Transmission Lines

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CANADA

Abstract - **A Monte Carlo model of the lightning performance of Manitoba Hydro's Nelson River HVDC transmission lines has been constructed in PSCAD/EMTDC Version 3. The values of key parameters are randomly drawn from user specified probability density functions (pdf's). Most significant of these are the pdf's of the positive and negative lightning stroke amplitudes which have been derived from actual data measured within a 1 km radius buffer of the lines. Estimates of the back flashover rate and shielding failure rate were calculated using various "zone-of-attraction" models. Of those tested, Eriksson's model yielded failure rates most consistent with our lightning correlated fault data.**

Keywords: Transient Analysis, Modelling, Lightning, Insulation Coordination, Monte Carlo, EMTDC/PSCAD.

I. INTRODUCTION

The principle difficulty in modelling the lightning performance of any overhead transmission line is the genuine variability of the key model parameters. Monte Carlo techniques accommodate these variabilities by accumulating the results of repeated computer simulations made with randomly drawn parameter values [1]. If the independent random variables are each drawn from realistic probability density functions (pdf's), and if the physical behaviour is accurately modelled then the computed failure rate (i.e. the number of runs resulting in failure v.s. the total number of runs) should be a reasonable representation of the actual lightning performance of the modelled line.

In this paper, the authors present a Monte Carlo model of the lightning performance of Manitoba Hydro's Nelson River HVDC transmission lines. These two bipolar transmission lines are parallelled on the same right-of-way for roughly 900 km. Bipole I is rated at ±450 kV and Bipole II is rated at ±500 kV. The random variables considered for this Monte Carlo analysis (namely the pre-ionization tower footing resistance, and the amplitude and rise time of the lightning current pulse) are drawn from user defined pdf's. Most notably, the pdf's of the positive and negative lightning stroke amplitudes are derived from a series of individual lightning stroke measurements collected by Environment Canada's Canadian Lightning Detection Network (CLDN) and analysed, at Manitoba Hydro, by means of the Fault Analysis and Lightning Location System (FALLS) program supplied by Global Atmospherics Inc. Thus lightning stroke statistics gathered within a 1 km radius buffer of the Nelson River transmission line corridor form the basis of the lightning challenge to a PSCAD/EMTDC Version 3 model of the conductor-tower-insulator-ground system. For simplicity and economy, only a single bipolar line was explicitly modelled on the assumption that the lightning performance of each bipolar line would be more or less the same.

Two modes of failure are considered: back flashover (a large magnitude strike to the tower) and shielding failure (a smaller magnitude strike to a pole conductor). The specific "point-of-contact" (i.e. shield wire, pole conductor, or earth) is selected in a semi-deterministic manner: an unbiased random lateral location for the stepped leader is input to an electrogeometric "zone-of-attraction" model which then determines the location of the return stroke. Outage statistics estimated by way of several different zone-of-attraction models are compared to lightning correlated outages in order to judge which of these models is best suited for predicting the lightning performance of the Nelson River HVDC transmission lines.

II. MODEL OVERVIEW

A hierarchical multi-layered graphical representation of the conductor-tower-insulator-ground system was implemented in PSCAD/EMTDC Version 3 (see Fig. 1). The multi-run feature of this software is used to generate a sufficient number of runs to allow a statistical Monte Carlo analysis (1 run = 1 lightning stroke).

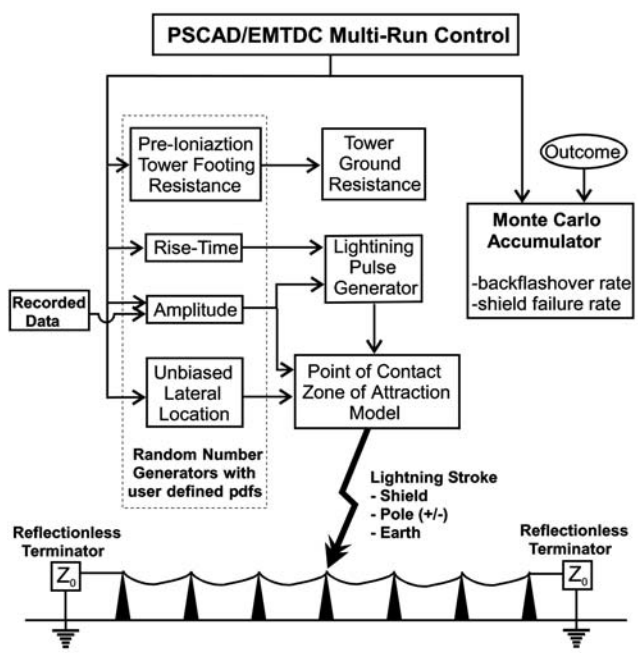

Fig. 1. PSCAD/EMTDC Version 3 Nelson River HVDC transmission line lightning model.

For each run, random number generators select values for the pre-ionization tower footing resistance and for the amplitude and rise time of the lightning current pulse based on user defined probability density functions (pdf's). The pdf of the stroke amplitude is of special importance since it is derived from actual stroke amplitudes measured within a 1 km radius of the Nelson River HVDC transmission lines. Transmission tower geometry, stroke amplitude, and initial location are fed into a zone-of-attraction model in order to determine the most likely point-of-contact between the stroke and the conductor-ground system (i.e. shield wire, pole conductor, or earth).

Insulator voltage at the struck tower consists of the primary surge and reflections from the three neighbouring towers on either side. Each tower is represented by a detailed travelling wave model. False reflections from the artificial truncation are eliminated by a multi-conductor surge impedance termination. The non-linear, time-dependent characteristics of the insulator strings are represented by the "Leader Progression Model" (LPM). The outcome of each run is stored in a "Monte Carlo Accumulator" which compares the number and nature of insulator flashovers to the total number of lightning strokes in order to obtain the rates of back flashover and shielding failure. Modelling details are discussed in the following section.

III. MODEL CONSIDERATIONS

A. Tower Model.

The geometry of the Nelson River transmission line corridor is shown in Fig. 2 [2]. The average span length is 457 m. For simplicity only a single bipole line is modelled.

The effects of fast fronted surges travelling in a tower were considered by modelling major tower sections (i.e. > 5 m in length) as constant parameter transmission lines. Surge impedance and propagation time along the various tower members are required in this model. The surge impedance is calculated using approximations given in [3]. The propagation time along a tower member is taken to be 3.92×10^{-9} sec/m. A 5 nsec simulation time step is used. Fig. 3 illustrates the graphical representation of the Nelson River HVDC tower structure. The tower was divided into five equivalent transmission line sections including the upper member, two crossarms, tower base, and the single equivalent of four parallel guy wires.

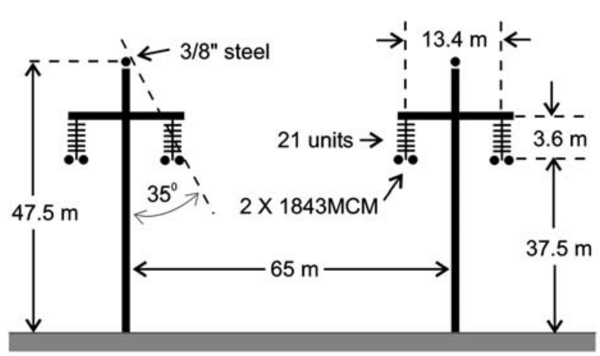

Fig. 2. Nelson River HVDC transmission line.

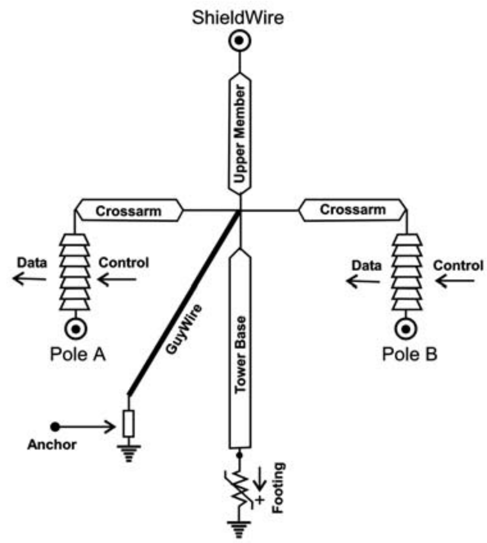

Fig. 3. PSCAD/EMTDC page component for a tower.

B. Reflectionless Line Terminations.

It was found that explicit representation of the transmission line beyond the three neighbouring towers to either side did not appreciably influence the voltages at the struck tower. Thus the detailed transmission line model is truncated as shown in Fig. 1. In order to prevent false reflections from the truncations, the line model is terminated into its multi-conductor surge impedance. The general n-conductor surge impedance is implemented as a network of impedances Z_{ij} , $i, j = 1,2,\ldots n$, defined as,

$$Z_{ij} = \begin{cases} \left(Y_{0,ii} - \sum_{k,k \neq i}^{n} Y_{0,ik} \right)^{-1} & for\ i = j \\ Y_{0,ij}^{-1} & for\ i \neq j \end{cases} [\Omega] \tag{1}$$

where Z_{ii} is the equivalent impedance between the i^{th} conductor and ground, Z_{ij} is the equivalent impedance between the i^{th} and j^{th} conductors, and $Y_0 = \{Y_{0,ij}\}$, $i, j = 1,2,\ldots n$, is the surge admittance matrix obtained from the surge impedance matrix $Z_0 = \{Z_{0,ij}\}$ $i, j = 1,2,\ldots n$, as $Y_0 = Z_0^{-1}$. The elements of the surge impedance matrix $Z_{0,ij}$ give the ratio of the voltage travelling wave on the i^{th} conductor to the (same direction) current travelling wave on the j^{th} conductor and are calculated by the high frequency approximation [3].

C. Insulator String.

Failure of the Nelson River HVDC transmission line was restricted to insulator flashover. The insulator string was modelled as a stray capacitance (0.476 pF for this 21 unit suspension insulator string) in parallel with a volt-time controlled circuit breaker as shown in Fig. 4. When the

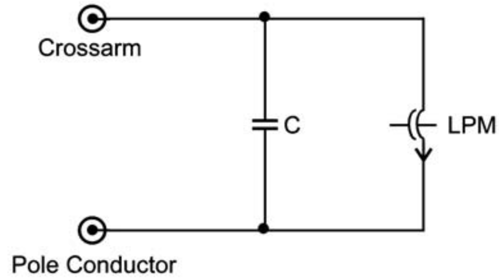

Fig. 4. Model of the insulator string.

voltage across the insulator string exceeds the insulator's volt-time characteristic as defined by the Leader Progression Model (LPM) flashover is simulated by closing the breaker. In other applications the authors have placed a surge arrester in parallel with the capacitor and a circuit breaker.

The insulator breakdown process is modelled in simulation time by the LPM. The LPM considers the progress of the breakdown leader as it crosses the surface of the insulator from its inception to the time that it actually bridges the insulator string. The leader progression begins after the voltage gradient across the unbridged insulation has exceeded the critical breakdown voltage gradient E_{50}. As the leader progresses, the voltage gradient across the unbridged insulator gap increases, this in turn increases the velocity of the leader. The recursive equations selected by CIGRE for the leader velocity $v(t)$ and unbridged gap length $x(t)$ are [4], [5],

$$v(t) = k_L\, e(t)\left(\frac{e(t)}{x} - E_{50}\right) \quad \left[{}^{m}\!/_{\sec}\right] \tag{2}$$

$$x(t) = x(t-\Delta t) - v(t-\Delta t)\Delta t \quad [m] \tag{3}$$

where $e(t)$ is the voltage across the insulator at time t, $x(t)$ is the distance of the unbridged insulation gap, and k_L is a characteristic constant. For air-porcelain insulators the suggested values are $k_L = 7.785 \times 10^{-7}\ m^2/(V^2 \cdot sec)$ and $E_{50} = 535.0\ kV/m$ [4]. As long as e/x exceeds the critical gradient E_{50} the leader will advance to bridge the gap; if the voltage gradient across the insulator string falls below E_{50}, then the leader development is arrested. Thus depending upon the voltage across the insulator string, the leader can advance, stop or retreat as it bridges the insulator string. This generalization of the volt-time characteristic is necessary for the treatment of arbitrary voltage wave shapes.

D. Tower Ground Resistance.

High magnitudes of lightning current flowing through the ground decrease the ground resistance significantly below the measured low current values. In general this is due to soil ionization increasing the effective size of the ground electrode. A simplified method for calculating the reduction in ground resistance is given in [4],[5]. As the current to ground increases, streamers are formed in the soil. These streamers evaporate the soil moisture and produce arcs. Within the streamer and arc zones, the soil resistivity decreases and the boundary of the ionization zone can be treated as that of a perfect conductor. Thus soil breakdown can be viewed as increasing the diameter and length of the ground rod. As the ionization increases the zone becomes more spherical. Thus after the critical field strength E_0 has been reached, the metallic grounding system is approximated as a hemispherical electrode with a radius which depends on the magnitude of the current to ground.

The current required to achieve the critical breakdown gradient is given by,

$$I_g = \frac{1}{2\pi}\frac{\rho E_0}{R_0^2} \quad [kA] \tag{4}$$

where ρ is the soil resistivity (Ω·m), E_0 is the critical gradient (kV/m) and , R_0 is the pre-ionization resistance (Ω). Once the current to ground exceeds this value the grounding resistance varies with the magnitude of the current to ground. The high current resistance for a concentrated ground is approximated by,

$$R_i = R_0\left[1 + \left(\frac{I_R}{I_g}\right)\right]^{-1/2} \quad [\Omega] \tag{5}$$

where I_R is the actual current to ground.

The base of the towers for the Nelson River HVDC transmission lines are attached to steel cradle buried in the ground. The guy wire anchors are cemented into the ground and were treated as an opened circuit. A PSCAD/EMTDC Version 3 component was developed to calculate each individual tower grounding resistance based on [4] and [5].

The low current tower footing resistance is not assumed to be constant over the entire length of the Nelson River HVDC transmission line. By varying the value of the footing resistance different geographic locations and seasonal variations can be modelled. Unfortunately no detailed studies were done of the tower footing resistance over any appreciable length of the transmission line. Therefore the value of the breakdown gradient E_0 was taken to be an average value, $E_0 = 400\ kV/m$ [4]. The soil resistivity ρ varies greatly over the length of the line, a typical value of 100 Ω·m was used.

E. Point of Contact

Given a measured density of lightning stokes within a narrow buffer around the transmission line, it is necessary to estimate the location of each stroke termination, i.e. shielding, pole conductor or earth. Essentially every object is assumed to have a zone-of-attraction such that any lightning stroke entering an object's zone-of-attraction will strike that object. In the case of several tall objects close together, lightning will strike the object with the largest and outermost zone-of-attraction. Effectively this object will shield the other objects from the lightning. Fig. 5 illustrates the zones-of-attraction considered for a single Nelson River transmission line tower. For this model we simplified the

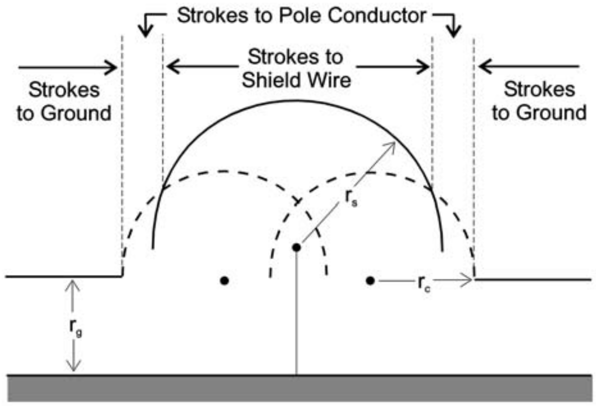

Fig. 5. Zones of Attraction for a bipolar HVDC transmission line tower.

tower geometry to only consider the zone-of-attraction projected from the shield wire at the tower top, the zones-of-attraction projected from each pole conductor at the insulators and, the zone-of-attraction of the ground.

Several different models for the zone-of-attraction have been developed. These models treat the zone-of-attraction as a 'strike distance' and are called electrogeometric models. For our simple model these strike distances include the strike distance to ground r_g, the strike distance to the shield wire r_s, and the strike distance to a pole conductor r_c. Five electrogeometric models were studied in this Monte Carlo simulation. In these models the strike distance depends on the peak lightning current amplitude I_m and is given by the general relationship $r_g = \beta C(I_m)^a$ [5]. Parameters β and a are determined by each model according to line geometry. The strike distances for a single Nelson River HVDC transmission line tower are listed in Table 1.

Table 1: Strike distances for the Nelson River HVDC transmission line [5].

Model	r_g	r_s	r_c
Young	$27\ I_m^{0.32}$	$1.071\ r_g$	$1.046\ r_g$
Love	$10\ I_m^{0.65}$	r_g	r_g
IEEE 1992 T&D	$9\ I_m^{0.65}$	$1.256\ r_g$	$1.256\ r_g$
Brown & Whitehead	$6.4\ I_m^{0.75}$	$1.274\ r_g$	$1.180\ r_g$
Eriksson	*-n.a.-	$6.8\ I_m^{0.74}$	$5.9\ I_m^{0.74}$

* In Eriksson's model, any lightning which does not strike the transmission tower strikes the ground by default [6].

For multi-conductor transmission lines, the zone-of-attraction model predicts a critical peak current amplitude below which shielding failure is possible. For peak lightning stroke current amplitudes at or above the minimum critical peak current amplitude the zones of attraction of each pole conductor are completely shielded by the zone-of-attraction of the shield wire and therefore the shield wire intercepts all lightning strokes directed toward the transmission line. For any peak lightning current amplitude below this critical value, the pole conductors are not completely protected by the shield wire and thus shielding failure is possible. Table 2 lists the critical peak current amplitudes predicted for the Nelson River HVDC transmission line tower.

Table 2: Critical peak lightning current amplitudes for the Nelson River HVDC transmission line towers.

Model	Critical Current (kA)
Young	25
Love	30
IEEE 1992 T&D	70
Brown & Whitehead	20
Eriksson	15

F. Lightning Stroke

The lighting stroke was modelled as a current impulse, idealised as a triangular wave. The rise time and amplitude were determined stochastically. Different amplitude pdf's were used for positive and negative lightning strokes as determined from the FALLS program. Because insulation failure occurs shortly after the lightning strike, the fall time (time to half the peak amplitude) was fixed at 100 μsec.

IV. MONTE CARLO SIMULATION

Lightning outage statistics are estimated by way of a Monte Carlo simulation, by which we mean a multi-run case in which the key model parameters (pre-ionization footing resistance, lightning stroke rise time, lightning stroke peak current amplitude, and lateral position of stroke), for each separate run, are randomly drawn from a pre-defined pool of values. Each individual run is considered to be an individual lightning challenge to the line. As the number of runs increases the ratio of insulator flashovers to the total number of runs approximates the actual lightning outage rate of the modelled line. Negative and positive lightning strokes are treated in separate Monte Carlo simulations. These separate outage rates are then weighted and added together to arrive at the total predicted outage rate. The Monte Carlo simulation was run for a total of 20,000 lightning strokes (10,000 strokes for both positive and negative lightning).

The pdf's for the pre-ionization tower footing resistance (Fig. 6) and for the lightning stroke rise time (Fig. 7) were derived from sensitivity studies, such that the range of lightning stroke amplitudes which resulted in insulator flashover corresponded to the observed range of fault-correlated lightning strokes. The pdf's for the amplitude of positive (Fig. 8) and negative (Fig. 9) lightning strokes were extracted from actual historical lightning stroke data collected within a 1 km radius buffer around the Nelson River transmission lines. The unbiased lateral strike location is equal likely to fall anywhere within the 1 km radius buffer; the actual point-of-contact is determined by the zone-of-attraction.

Random parameters (i.e. pre-ionization tower footing resistance, lightning rise time, and peak current amplitude) are generated according to the statistics of their respective

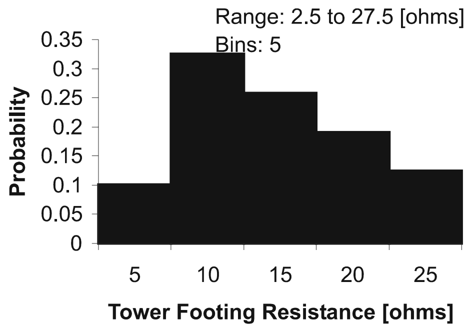

Fig. 6. PDF for the tower footing resistance.

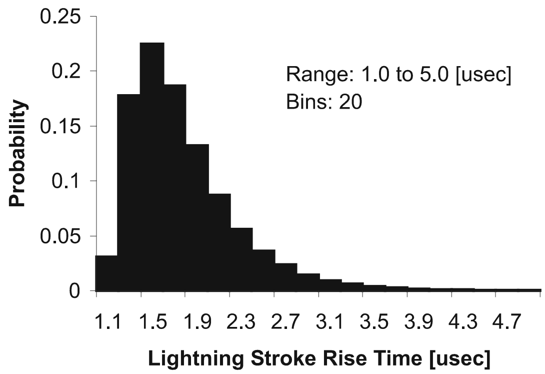

Fig. 7. PDF for the lightning stroke rise time.

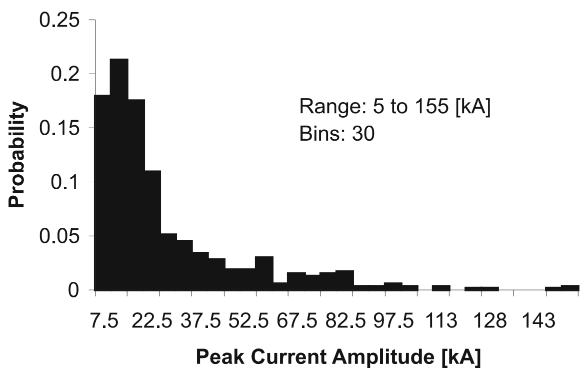

Fig. 8. PDF for positive lightning stroke peak current amplitude.

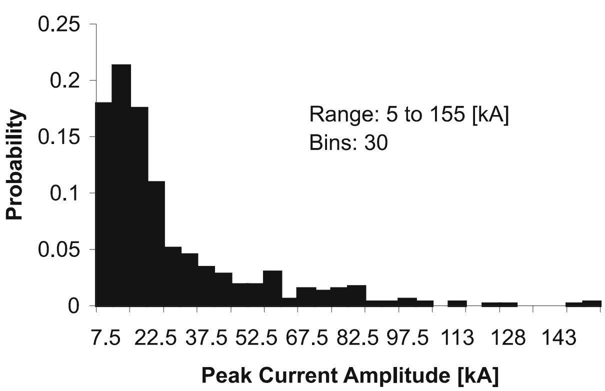

Fig. 9. PDF for negative lightning stroke peak current amplitude.

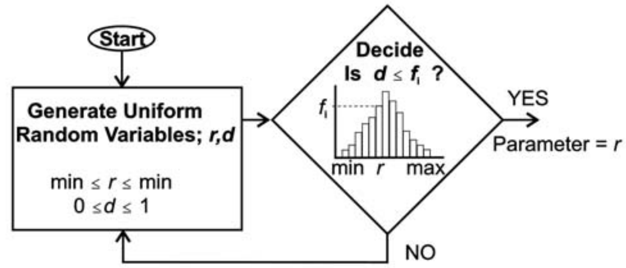

Fig. 10. Generation of random parameter with user specified pdf, *f(r)*.

pdf's. An "acceptance or rejection" process for the generation of random parameters is shown in Fig. 10 and outlined as follows. The expected range of a random parameter is divided into bins and each bin is assigned a probability of occurrence f_i. At the start of each simulation run, and for each random parameter, a uniformly distributed random variable r is generated as a candidate value for the desired parameter. A second random number d, the decision variable uniformly distributed between 0 and 1, is generated and compared with the probability f_i assigned to the bin into which the candidate r had fallen. If the decision variable is less than the assigned bin probability f_i then r is selected as the value of the parameter. If the decision variable d is greater than f_i then r is rejected and the procedure is repeated.

During each run the Monte Carlo lightning model generated a code which indicated where the lightning stroke struck (shield wire, +ve or –ve pole conductor, or earth) and whether or not an insulator flashover occurred. For each run this code and the values of the random parameters were recorded in a file. Analysing this file allowed us to determine the predicted lightning induced outage rates.

V. RESULTS

Using fault data for the Nelson River HVDC transmission lines collected between 1998 to 2000, faults were correlated to lightning strikes occurring at the same time and location. Over this period of time the FALLS program found 5066 negative lightning strokes and 530 positive lightning strokes (9.56 to 1) within a 1 km radius buffer of the transmission line. Out of these lightning strikes, only 6 are found to have caused failure.

The magnitudes of the outage correlated lightning strokes follow a bimodal distribution as shown in Fig. 11, suggesting that faults are due to both shielding failures and back flashovers. Shielding failures are due to lightning strokes having peak current amplitudes below the critical values given Table 2 such that they are able to "slip past" the shield wire to strike the pole conductor. Back flashovers are due to lightning strokes intercepted by the shield wire and of sufficient peak current magnitude to cause the insulator string to flashover. This leaves a range of medium lightning peak current amplitudes in which no failures occur. Table 3 lists the measured lightning induced failure rates normalised for 10,000 lightning strokes.

The Monte Carlo simulation of lightning strikes to the

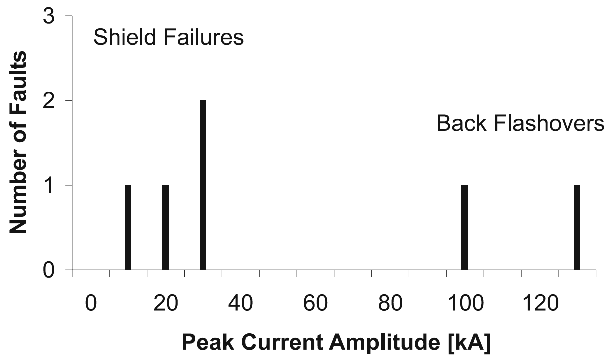

Fig. 11. The number of lightning induced faults at a given lightning peak current amplitude as measured by the FALLS program.

Nelson River HVDC transmission line predicted very different failure rates depending on which model was used for the zone-of-attraction. These failure rates are listed in Table 3. For this specific example the electrogeometric models of Young's, Love's and, the IEEE 1992 T&D greatly over predicted the number of shielding failures. On the other hand the two remaining models, Brown & Whitehead and Eriksson's predicted failure rates closer to those actually observed, however the Brown & Whitehead model predicted a disproportionately high ratio of back flashovers to shielding failures. Of the models tested, Eriksson's model yielded failure rates most consistent with the recorded data.

Table 3. Back flashover rates and shielding failure rates per 10,000 lightning strikes.

Model	Back Flashovers	Shielding Failures
Young	2	11.2
Love	3.3	58.5
IEEE 1992 T&D	6	75.5
Brown & Whitehead	7.5	3
Eriksson	2.1	6.2
***Measured**	3.6	7.1

*It must be noted that the measured results combine outages on both bipole I and bipole II while the calculated estimates apply to our simple single bipolar line model. The extent to which the zones of attraction of the two parallel bipolar lines overlap and the effect of this overlap has not been accounted for in this simple model.

VI. CONCLUSION

A Monte Carlo model of the lightning performance of Manitoba Hydro's Nelson River HVDC transmission lines has been constructed in PSCAD/EMTDC Version 3. The values of key parameters are randomly drawn from user specified probability density functions (pdf's). Most significant of these are the pdf's of the positive and negative lightning stroke amplitudes which have been derived from actual data measured within a 1 km radius buffer of the lines. Estimates of the back flashover rate and shielding failure rate were calculated using various zone-of-attraction models. Of those tested, Eriksson's model yielded failure rates most consistent with our lightning correlated fault data. The extent to which the zones of attraction of the two parallel bipolar HVDC transmission lines overlap, and the effect of this overlap on the estimated failure rates have not been taken into account in this simple single bipolar transmission line analysis.

VII. REFERENCES

[1] J. G. Anderson, "Monte Carlo Computer Calculation of Transmission-Line Performance", *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-80, pp. 414-419, 1961.

[2] C.V. Thio, "Nelson River HVDC Bipole-Two, Part I – System Aspects", *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-98, no. 1, Jan/Feb 1979.

[3] EPRI, *Transmission Line Reference Book*, 345 kV and Above, Second Edition, Revised, Electric Power Research Institute, Inc., 1987

[4] A. R. Hileman, *Insulation Coordination for Power Systems*, Marcel Dekker, Inc., New York, 1999.

[5] Working Group 01 (Lightning) of Study Committee 33 (Overvoltages and Insulation Co-ordination) "Guide to Procedures for Estimating the Lightning Performance of Transmission Lines" Cigre Technical Brochure 63, October 1991.

[6] A. J. Eriksson, "An Improved Electrogeometric Model for Transmission Line Shielding Analysis", *IEEE Transactions on Power Delivery*, vol. PWRD-2, No.3, July 1987.