

# Simulation Study of a Lightning Initiated 3-Phase Fault on a 138 kV Wood Pole Line without Shielding

M. Armstrong, P. Mayer, K. Mai

**Abstract--** BC Hydro's transmission lines operate at 69 kV to 500 kV and are mainly unshielded from lightning. The majority of 69 kV, 138 kV, and 230 kV lines are wood pole lines that have shown very good lightning performance over the years, mainly due to low keraunic levels, incidental shielding of the transmission right-of-ways by surrounding trees, and reliance on the arc quenching properties of wood. A recent rare example of a 3-phase fault on one of BC Hydro's 138 kV wood pole lines is presented in this paper. This paper explains the mechanisms that led to a 3-phase fault on the 138 kV line in question, supported by EMTP based simulation, and provides insight why this is such an unusual event in BC Hydro's system.

**Keywords:** arc quenching, wood pole lines, lightning performance, EMTP modelling

## I. INTRODUCTION

This paper provides an overview of BC Hydro's transmission network and explains how the lightning performance of transmission circuits varies in different regions of British Columbia, Canada, focusing on the performance of wood pole lines.

The number of strokes collected by BC Hydro's power lines is low by virtue of both the low keraunic levels and the effect of shielding by trees. The provision of shield wires is relatively expensive because of heavy snow loading, which significantly increases the loads on the supporting structures. Furthermore, any improvement in lightning performance available from shielding is limited because of the prevailing high soil resistivities, which make it both difficult and expensive to achieve low grounding resistances. For example, the average soil resistivity in British Columbia (BC) is around 1000  $\Omega\text{m}$ , but soil resistivity as high as 20 000  $\Omega\text{m}$  has been recorded in mountainous regions of BC. In view of the above, BC Hydro has historically used unshielded lines.

The BC Hydro transmission system covers a wide range of voltages starting from the subtransmission level at 69 kV to high voltage levels at 138 kV, 230 kV, and 287 kV, and extra

high voltage levels at 360 kV and 500 kV. Most transmission lines 230 kV and below are wood pole lines and have traditionally shown very good lightning performance despite their lack of shield wires. Together with the effect of shielding by trees, the arc quenching capability of wood contributes to this good performance. A sufficient length of wood will conduct a lightning surge while blocking any 60 Hz current from following.

The topic of this paper is the performance of the 138 kV transmission lines that exist in all regions of BC Hydro's system. A keraunic map of BC is depicted in Fig. 1.



Fig. 1. Keraunic map of British Columbia

BC Hydro's 138 kV transmission lines are built with a variety of structures. Some typical structure types are the H-frame and wishbone designs, as shown in Fig 2. In total, there are 4300 km of 138 kV wood pole lines, compared to 550 km of steel 138 kV lines, throughout BC Hydro's system.

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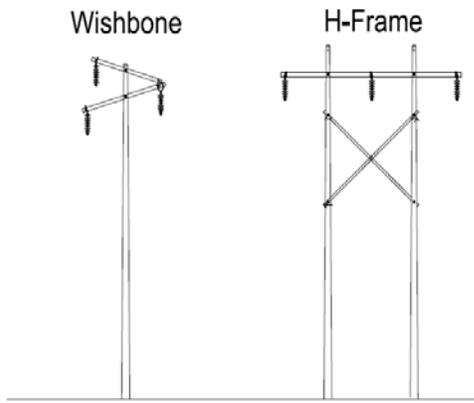


Fig. 2. BC Hydro 138 kV wood pole structure types

In the past 10 years of operation, 283 outages – the majority of them momentary – have been attributed to lightning on wood pole lines in the 138 kV network.

TABLE I  
LIGHTNING PERFORMANCE OF BC HYDRO 138 kV WOOD POLE TRANSMISSION LINES

Length [km]	4300
Momentary outages	230
Sustained outages	53
Total outages	283
Total outage duration [h]	118.6
Average outage duration [h]	2.2
Momentary outages per 100 km per year	0.5348
Sustained outages per 100 km per year	0.1232

## II. CASE STUDY

A lightning initiated 3-phase fault was recorded on June 2014 on a 138 kV wood pole line with H-frame construction. The line is just over 100 km long and is located in the Southern Interior region of British Columbia. Based on the keraunic map this area of BC experiences, on average, 12 thunderstorm days per year, or an approximate ground flash density of one flash/km<sup>2</sup>/year.

For this particular line, 13 lightning initiated momentary outages were recorded in the past 10 years, three of which were 3-phase faults. Seven of the recorded faults were line-to-ground faults, while three were phase-to-phase faults.

The most likely location of the studied 3-phase fault was determined from the fault records. Based on the timing of the fault, information was retrieved and correlated with the lightning strokes recorded in the vicinity of the line (Fig. 3). Lightning data was obtained from Indji Systems' Indji Watch. The fault record for this event is shown in Fig 4.

The lightning performance of this unshielded line was analyzed using Mousa's Electrogeometric Model [6]. The contribution of the surrounding forests was taken into account [4], resulting in an expected total of 5 outages per year per 100 km of the line. The actual recorded lightning performance

of this specific line was around 1.3 outages per year per 100 km of the line. This improved actual lightning performance can be attributed to the arc quenching properties of wood. The typical geometry of a 138 kV line with H-frame construction is shown in Fig. 5.

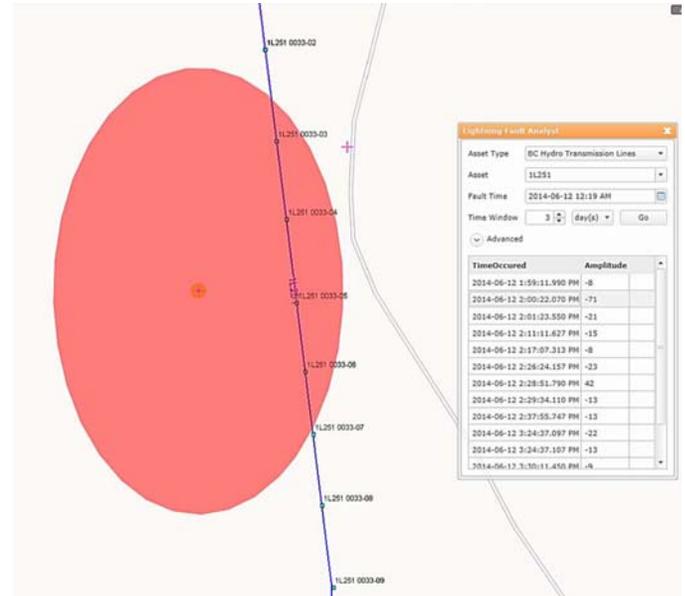


Fig. 3. Lightning stroke location (99% confidence ellipse) overlapping the location of the 138 kV circuit at the time of a 3-phase fault

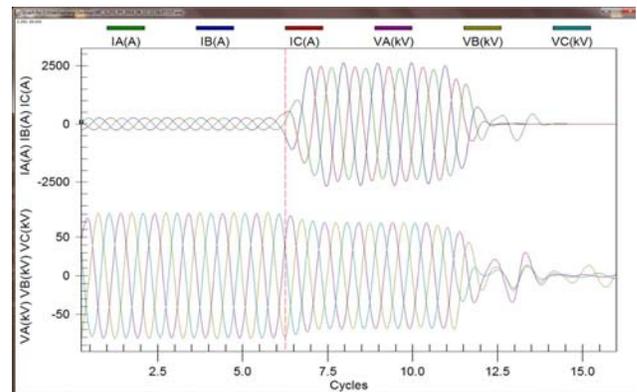


Fig. 4. Fault record for the studied 138 kV 3-phase fault

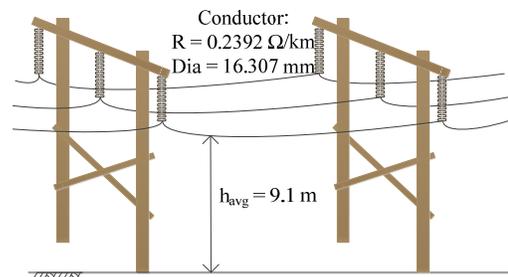


Fig. 5. Typical span of a 138 kV transmission line with H-frame wood pole structures

### III. EMTP MODEL AND SIMULATION RESULTS

The majority of lightning initiated events on wood pole lines are either undetected by protection relays or result in a single phase to ground fault. Modelling of wood pole structures attempts to explain the different mechanisms by which a lightning stroke can cause a single phase-to-phase or 3-phase fault.

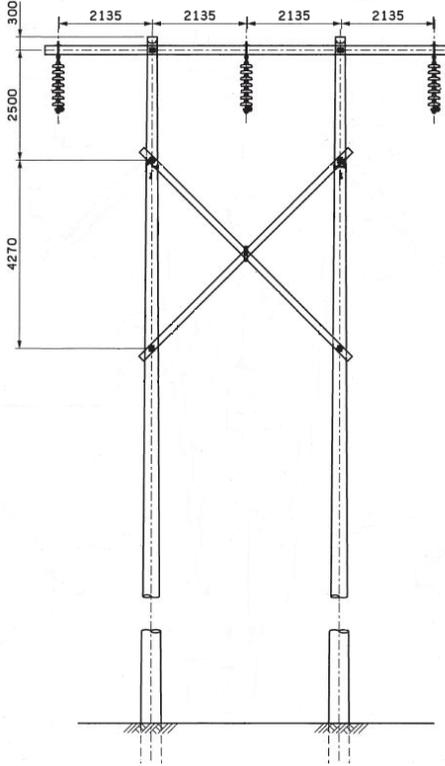


Fig. 6. 138 kV wood pole suspension tangent structure (H-frame)

The model was created in EMTPWorks v.2.6.1 and run using the EMTP-RV engine. The lightning stroke was assumed to strike an outer phase conductor and was simulated with a current source in parallel with a fixed 2 k $\Omega$  resistor to represent the return stroke impedance [7].

Using generalized impulse flashover data from [8], the combination of the outer insulator strings and outer crossarm sections were lumped together and their flashover was modeled using a single controlled switch and parallel capacitor. Flashover of the centre phase was modeled as a crossarm-insulator combination on one side (arm2) and a section of wood on the other side (arm3). Lumping the wood crossarm sections together with the insulator strings made it possible to use test data from [8] that capture the nonlinear effect on breakdown voltage when wood and porcelain are combined.

The switch representing the insulator-crossarm sections closed when the voltage across the parallel 2pF capacitor exceeded 850 kV. The arm3 switch closed when the voltage across its 5 pF capacitor exceeded 600 kV.

The 138 kV phases were modeled by a 50 km long wide-band transmission line model [3] in each direction. In one direction the line was terminated with a 138 kV voltage source, and in the other direction it was terminated with a resistor matching the surge impedance of the transmission line. The conductor details of the line are shown in Fig.5 and other geometry is shown in Fig.6.

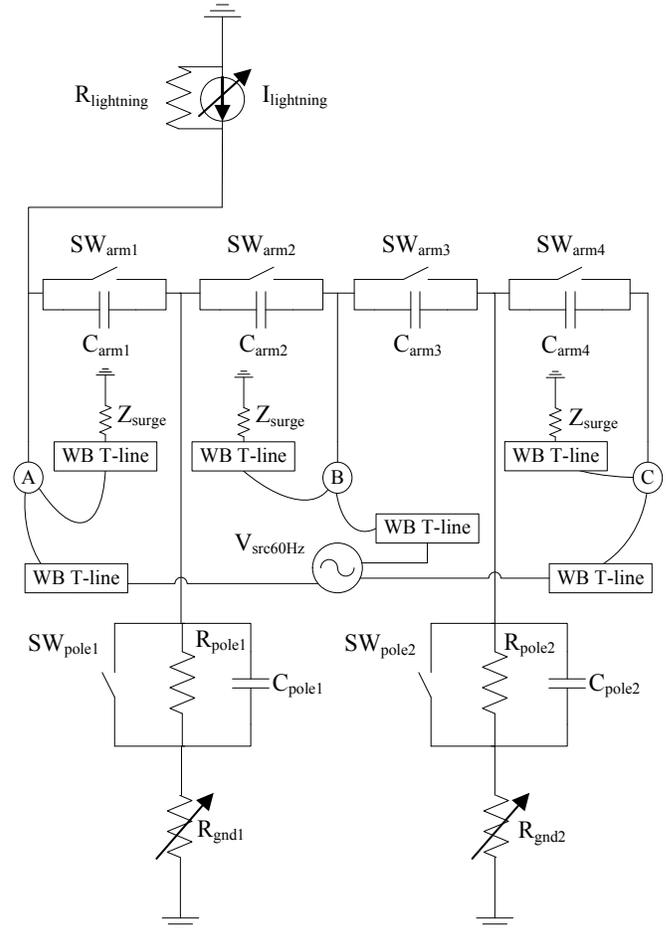


Fig. 7. Electrical model of a 138kV H-frame wood pole structure

The vertical wood poles that support the crossarm were modeled as resistors with a parallel capacitance. Values of 7.5 M $\Omega$  and 3pF were used [1]. Breakdown was simulated with a controlled switch in parallel with the pole resistance. Breakdown across the pole was assumed to occur if the voltage exceeded 500 kV.

When lightning current enters the ground at the base of the pole the soil may break down and create an ionized hemisphere [9]. The resistance of the ionized hemisphere is represented by a variable resistor at the base of each pole. The resistance to ground of the hemisphere will depend on the injected current, the ionization gradient, and the soil resistivity. In this model, a soil resistivity value of 1000  $\Omega$ m was used. The resistance of the pole base decreases as the size of the ionized hemisphere increases.

#### IV. SIMULATION RESULTS

A variety of lightning strokes were simulated on the presented electrical model of a 138 kV wood pole structure. The effect of the stroke's arrival time relative to the voltage angle of the struck phase was investigated along with the effect of stroke magnitude. Three types of sustained faults were identified: single line-to-ground faults (SLG) where the crossarm and the wood pole broke down, phase-to-phase faults (2LG), and three-phase faults (3PH). The results are shown in Table III.

TABLE II  
OBSERVED LIGHTNING INITIATED OUTAGE EVENTS ON THE STUDIED 138 kV  
WOOD POLE TRANSMISSION LINE

Outage Date	Fault Type	Stroke Amplitude [kA]
2014-06-12	3PH	-71
2013-08-11	3PH	-53
2012-07-20	2LG	-34
2013-08-11	SLG	-26
2011-05-29	SLG	-21
2013-08-04	SLG	-14
2009-07-30	SLG	-14
2014-06-02	SLG	-9

Nomenclature: SLG (single line-to-ground), 2LG (two phase-to-ground), 3PH (three-phase)

TABLE III  
SIMULATED ELECTRICAL FLASHOVER OF 138 kV WOOD POLE STRUCTURE

Angle [°]	Stroke peak amplitude [kA]						
	-10	-15	-20	-30	-40	-50	-60
0	SLG	SLG	SLG	SLG	2LG	3PH	3PH
60	SLG	SLG	SLG	SLG	SLG	2LG	3PH
120	SLG	2LG	2LG	2LG	2LG	2LG	3PH
180	2LG	2LG	2LG	2LG	2LG	2LG	3PH
240	2LG	2LG	2LG	2LG	2LG	2LG	3PH
300	2LG	2LG	2LG	2LG	2LG	3PH	3PH

Nomenclature: SLG (single line-to-ground), 2LG (two phase-to-ground), 3PH (three-phase)

#### V. CONCLUSIONS

The electrical properties of wood poles and modelling for the purpose of a lightning study are discussed in this paper. This paper describes how the lightning detection system was used to correlate the power system events around the time of a fault with lightning activities in the area.

Recent changes in BC Hydro's wood pole structure designs, such as the replacement of wood cross arms and wood cross braces with steel and more stringent requirements for bonding and grounding, are expected to significantly impact the lightning performance of new lines. Understanding the electrical behavior of wood under lightning discharge conditions is thus essential in the consideration of new line designs.

This paper proposes a method for validating the electrical model of a wood pole line against the data obtained from real-life events recorded by protection relays and lightning

detection networks. In this way, the model can account for typical local conditions encountered during the lightning season.

#### VI. ACKNOWLEDGMENT

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#### VII. REFERENCES

##### Periodicals:

- [1] I. M. Dudurych, T. J. Gallagher, J. Corbett, M. V. Escudero, "EMTP analysis of the lightning performance of a HV transmission line," Generation, Transmission and Distribution, IEE Proceedings- , vol.150, no.4, pp.501,506, 14 July 2003.
- [2] J. A. Martinez- Velasco and F. Castro- Aranda. Modeling of Overhead Transmission Lines for Lightning Studies. International Conference on Power Systems Transients (IPST'05) in Montreal, Canada, June 19-23, 2005
- [3] A. Morched, B. Gustavsen, M. Tartibi "A universal model for accurate calculation of electromagnetic transients on overhead lines and underground cables", . IEEE Trans. Power Del., vol. 14, no. 3, pp. 1032 -1038, July 1999.
- [4] A. M. Mousa and K. D. Srivastava, "Effect of shielding by trees on the frequency of lightning strokes to power lines", *IEEE Trans. Power Del.*, vol. 3, no. 2, pp.724 -732 1988
- [5] A. M. Mousa and K. D. Srivastava, "The lightning performance of unshielded steel-structure transmission lines", *IEEE Trans. Power Del.*, vol. 4, no. 1, pp.437 -445 1989
- [6] A. M. Mousa and K. D. Srivastava "An Improved Electrogeometric Model for Transmission Line Shielding Analysis", *IEEE Trans.*, vol. PWRD-2, no. 3, pp.880 -881 1987

##### Books:

- [7] EPRI, 2005, Transmission Line Reference Book, 200 kV and Above, Third Edition.
- [8] M. Darveniza, Electrical Properties of Wood and Line Design, 1980

##### Papers from Conference Proceedings (Published):

- [9] A. M. Mousa, "Breakdown Gradient of the Soil Under Lightning Discharge Conditions", presented at 1992 International Aerospace and Ground Conference on Lightning and Static Electricity, Atlantic City, New Jersey, U.S.A., 6 – 8- October, 1992.
- [10] A. M. Mousa and K. D. Srivastava, "The distribution of lightning strokes to towers and along the span of shielded and unshielded power lines", *Canad. J. Electr. Comput. Eng.*, vol. 15, pp.115 -122 1990

##### Standards:

- [11] A. Mousa et al. BC Hydro Engineering Standard "Lightning Performance and Lightning Protection", 2013, BC Hydro internal document