MODELLING OF ICE STORMS FOR POWER TRANSMISSION RELIABILITY CALCULATIONS

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Abstract - This paper describes a new technique of modelling adverse weather for power system reliability calculations. The reliability calculation is based on a Monte-Carlo technique where each scenario represents a certain weather situation with certain parameters. For each scenario a model of the adverse weather is needed and in this paper a model based on geographically moving winds and ice storms is developed. The benefit of this is that it is possible to estimate the time difference between mean times to failure in different lines, not only the outage risk. For each scenario a weather impact model is also required, where the risk of transmission outage is connected to the weather situation. The here-developed model connects the direct wind impact with the integrating impact from the ice storm. The developed method is applied to a numerical example.

Keywords - Weather model, ice storm, tower, reliability

1 INTRODUCTION

THE technical infrastructure is of crucial importance for a modern society to function. Electric power supplies are of particular importance and society's dependence on electrical energy, communications and information technology tending to increase. Power supply is also a condition for continued economic growth and national security. At the same time users, both industry and households, have a confidence in technical infrastructure functionality and small preparedness for outages in the power network [1]. An interruption in the power system can have many causes: technical faults, operational problems, adverse weather, vandalism. One important cause of transmission line outage is adverse weather. An ice storm is an extreme situation which occur very infrequently and cause extensive damage when it does. A recent example is the ice storm that hit eastern Canada and Northeastern United States in January 1998 and caused a crisis that lasted more than five weeks. The 1998 ice storm is considered to be the worst in modern time in Canada [2].

In order to mitigate severe consequences of future ice storms it is essential to be able to estimate these consequences based on knowledge of the technical system and the severeness of the ice storm.

Methods for including the impact of weather on power reliability calculations have been studied earlier. The most widely used model is the two-state (normal and adverse) weather model that uses constant failure and repair rates [3]. Many studies assume the entire network to be in the same weather environment, a reasonable assumption for geographically constrained distribution networks but not for transmission networks. In [4] a model applicable to transmission networks is described. A wide range of weather severities are considered, but the distribution of severity levels is discreet and the exposed area has to be divided into regions that are equally affected. A method for estimating the risk to transmission system components due to ice storms is described in [5]. The impact on the towers is assumed to be deterministic, the towers break down at a given ice load that is decided based on experiments. A standardized risk estimation spreadsheet developed by British Columbia Transmission Corporation (BCTC) is used to calculate the risk of three different severity levels of ice storms. Since Canada experienced a severe ice storm in 1998 many case studies are performed on test network based on Canadian conditions. In [6] the sequence of failure of an experimental distribution line is examined. Another example is [7] where the status of existing transmission line components are considered.

The approach used in this paper is to estimate the reliability with a Monte-Carlo technique where each scenario represents a certain weather situation. For each scenario a model of the adverse weather is needed and the here developed model uses geographically moving winds and ice storms. For different scenarios the stochastic weather parameters, such as size, strength, speed and direction can change. A description of the overall simulation method is found in chapter 2, while the weather model is found in chapter 3. One benefit of this approach is that it is possible to estimate the time difference between the outages in different lines, not only the outage risk. For each scenario a weather impact model is also required, where the risk of transmission outage is connected to the weather situation. This vulnerability model for the components also include a Monte-Carlo technique for deciding whether a failure occur or not. The model presented in this paper connects the direct wind impact with the integrating impact from the ice storm, see chapter 4. The developed method is finally applied to a numerical example in chapter 5.

It has been difficult to find simulation data therefore a discussion with experienced people from industry was necessary and the references are partly of this kind.

2 GENERAL APPROACH

The studied area or network is called area of interest and contains components, such as towers and line segments. These components may break down under influence of severe weather. The extent to which a segment is affected depends on vulnerability of components and severity, direction and moving speed of severe weather. Because of the complexity of modelling the influence of severe weather in area of interest we only consider lines, divided into segments. A segment can for example consist of the line between two towers and one of the towers, but it can also represent longer parts of the line.

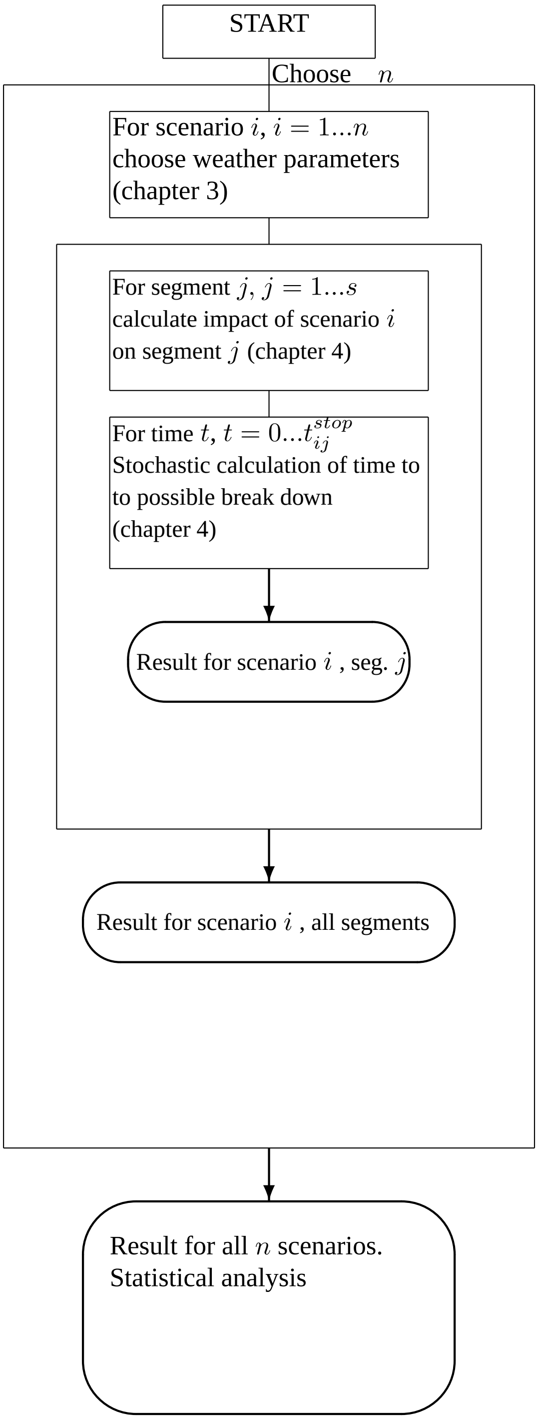


Figure 1: Flow chart of proposed method.

Denote the number of scenarios n and let the total number of segments be s. The time when the whole severe weather i has passed segment j is denoted t_{ij}^{stop}. The general modelling approach in this paper can be described by the flow chart in figure 1.

3 MODEL OF SEVERE WEATHER

Ice storms are freezing rain coating everything in ice. Since the largest precipitation occurs in the centre of storms, a circular model with the largest strength in the middle can be applied [8]. The function of two variables below has suitable properties for being a basic model for describing wind and ice load.

$$f(x,y) = A\exp\Big(-\frac{1}{2}\Big(\Big(\frac{x-\mu_1}{\sigma}\Big)^2 + \Big(\frac{y-\mu_2}{\sigma}\Big)^2\Big)\Big) \quad (1)$$

A is the amplitude, that is the severity level in the center of the weather. The center of the weather has coordinates (μ_1, μ_2).

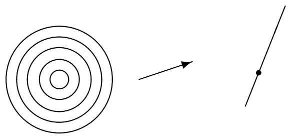


Figure 2: Weather approaching a line

Each segment is exposed to certain load functions that depend on which intensities of the weather meet the segment, and for how long. Observe that a segment does not need to meet all severity levels, and some part of the line may not be hit at all, see figure 2. A load function corresponding to point (x_j, y_j) where the centre moves as the functions $(\mu_1(t), \mu_2(t))$ can be calculated from

$$L(x_j, y_j, t) = \\ A\exp\Big(-\tfrac{1}{2}\Big(\Big(\tfrac{x_j-\mu_1(t)}{\sigma}\Big)^2 + \Big(\tfrac{y_j-\mu_2(t)}{\sigma}\Big)^2\Big)\Big). \quad (2)$$

The strength, or severity level, of the weather depends on ice load and wind load. These loads are modelled with $L(x_j, y_j, t)$, but with different parameters.

3.1 Wind load

Wind force is often treated as a mean value, for example the mean value of measured wind force during a typical ten minutes period. Wind force or wind load in this paper refer to the instantaneous wind force inside severe weather also called gust. The maximum wind force corresponds to the amplitude in equation (1).

Because the wind force is zero in the absolute center of a storm; equation (1) can not be used directly. By subtracting an extra function with less amplitude and smaller σ a more realistic model is achieved [8]. The wind load function, L_W, for segment (x_j, y_j) becomes as in equation (3).

$$L_W(x_j, y_j, t) = w(t)\Big[\\ A_1\exp\Big(-\tfrac{1}{2}\Big(\Big(\tfrac{x_j-\mu_x(t)}{\sigma_x}\Big)^2 + \Big(\tfrac{y_j-\mu_y(t)}{\sigma_y}\Big)^2\Big)\Big) \\ -A_2\exp\Big(-\tfrac{1}{2}\Big(\Big(\tfrac{x_j-\mu_x(t)}{\sigma_x}\Big)^2 + \Big(\tfrac{y_j-\mu_y(t)}{\sigma_y}\Big)^2\Big)\Big)\Big].$$

$$(3)$$

$L_W(t)$ for a particular segment is shown in figure 3, this figure can also represent a cross-section of wind with distance on the x-axis but a transformation of the time in seconds to distance in m by the formula

$$\text{distance } [m] = \text{speed } [m/s] \times \text{time } [s]$$

is needed.

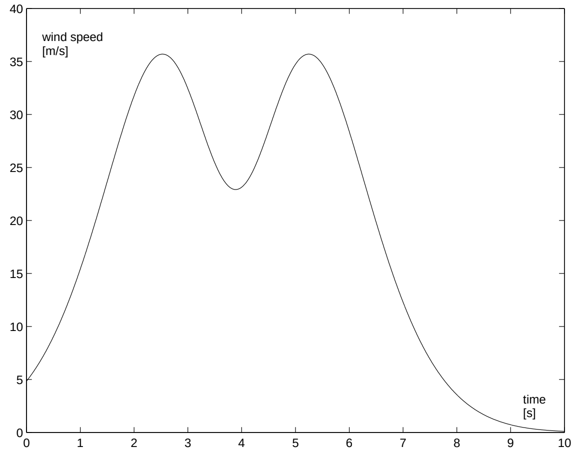
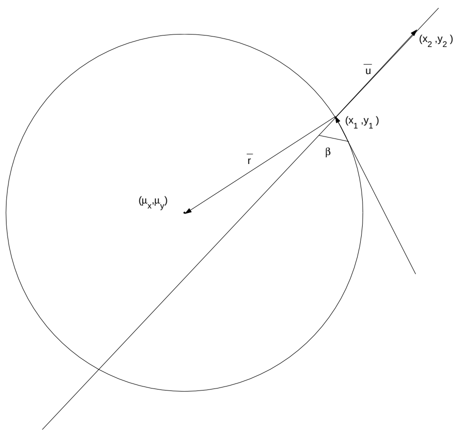


Figure 3: A wind load function or a cross section of wind.

$w(t)$ in equation (3) is the wind factor needed to consider the impact of the angle, β, by which the wind force hit the line. Wind force perpendicular to the line is the worst case, to include this in the model the perpendicular component of the wind force is used.



Let the segment have coordinates (x_1, y_1) and the centre of the weather have coordinates (μ_x, μ_y) at time t and choose an arbitrary point on the line with coordinates denoted (x_2, y_2) such that the angle α between the vector $\overline{r} = (x_1, y_1), (\mu_x, \mu_y)$ and $\overline{u} = \overline{(x_1, y_1), (x_2, y_2)}$ is between 0 and π. Then α is given from $\cos\alpha = \frac{\overline{r u}}{|\overline{r}||\overline{u}|}$ and $\beta = \frac{\pi}{2} - \alpha$ if $\alpha \leq \frac{\pi}{2}$ and $\beta = \alpha - \frac{\pi}{2}$ if $\alpha > \frac{\pi}{2}$, since the wind force is perpendicular to $\overline{r}$. β is always between 0 and $\frac{\pi}{2}$ and a function of time for each segment. The perpendicular component of the wind force is then achieved from multiplication by the wind factor as in equation (3).

$$w(t) = \sin\beta(t) \tag{4}$$

When the the wind force is parallel to the line, i.e when $\beta = 0$ the wind factor is 0. Wind parallel to a line is therefore not contributing to a break down, this is realistic since wind parallel to a line even can reduce the ice thickness [9]. The wind factor is 1 when the line is hit by perpendicular wind force, i.e. $\beta = \frac{\pi}{2}$.

3.2 Ice loading

If the conditions are such that we get ice loads on the line, the situation becomes more severe. Let the speed by which the ice build up on components ($[mm/h]$) also be modelled with a two parameter function. For an example of a cross-section, see figure 4.

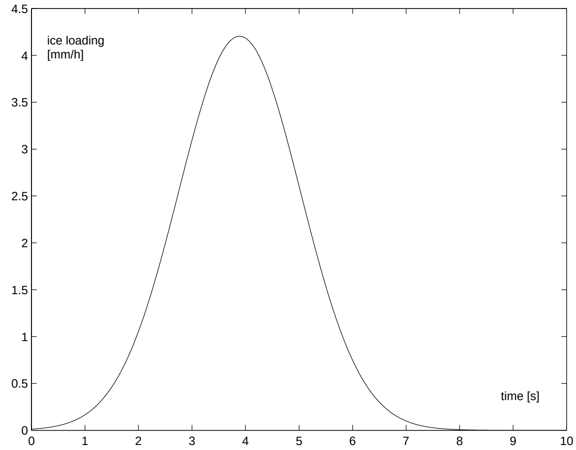


Figure 4: Ice build up function for a particular segment or a cross-section of ice.

Denote the ice load function for a particular segment $L_I(t)$, it corresponds to the total ice on the segment (x_j, y_j) at time t and is achieved by integration of the ice build up function for this segment.

$$L_I(x_j, y_j, t) = \int_0^t A_3 \exp\left(-\frac{1}{2}\left(\left(\frac{x_j - \mu_x(u)}{\sigma_x}\right)^2 + \left(\frac{y_j - \mu_y(u)}{\sigma_y}\right)^2\right)\right) du. \tag{5}$$

The ice built up continuously. t^{stop} is defined as the time when $L_I(t)$ is about equal to $L_I(t+\epsilon)$ for a small positive ϵ, i.e the time when the ice layer no longer increase. t^{stop} is needed because the melting process is not considered.

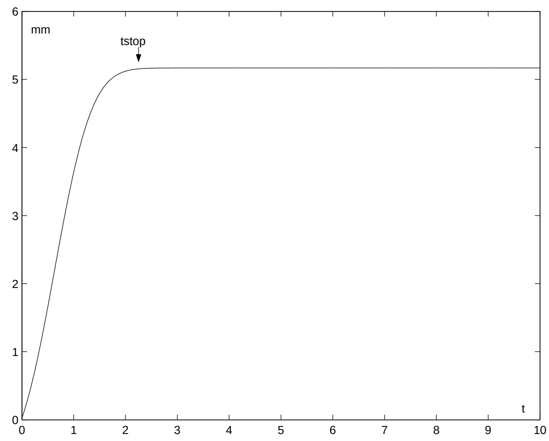


Figure 5: $L_I(t)$ for a particular segment.

3.3 Size of weather

The spreading of a two parameter function as (1) is infinite. Define normal weather as weather with severity level less than $\frac{A}{k}$, for some k. This means that the radius of severe weather, R, is the distance from the center to the first value smaller than $\frac{A}{k}$. The size of the severe weather is optional and varies with σ and k.

3.4 Weather moving speed

The weather moving speed, V_h, differs from the size of the wind force. The wind force does not help the weather as a whole forward, instead it determines the stress level to which the transmission lines are subjected, together with other varieties such as ice load. The moving speed describes how fast the weather is moving through the exposed area with V_h here assumed constant. Weathers move in direction from high pressure towards low pressure. On the north side of the globe the wind is blowing anti-clockwise around a low pressure due to the earths rotation and Coriolis forces.

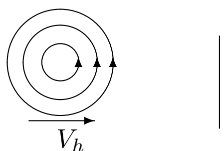


Figure 6: Wind around a low pressure

The centre of the weather located in $(\mu_x(t), \mu_y(t))$ at time t moves according to equation (6).

$$\begin{aligned} \mu_x(t) &= \mu_x(0) + V_h \cos(\Theta)t \\ \mu_y(t) &= \mu_y(0) + V_h \sin(\Theta)t, \end{aligned} \tag{6}$$

where Θ is as in figure 7 and $V_h = V_{hI}$ for the ice part of the weather and $V_h = V_{hW}$ for the wind part. Moving speed and angle for the ice weather may be different from speed and angle for the wind weather.

Figure 7: Definition of moving direction

3.5 Stochastic modelling of weather

The size of severe weather(R) is random within a suitable range. The part of the weather that contains ice is typically smaller than the wind weather. The speeds by which the ice build up and the wind load is given from meteorological data. The ice build up function may be chosen less symmetric than the function used for modelling the properties of wind load because specific weather conditions are necessary for ice loading, precipitation and temperature are central.

V_h is a constant, determined from known weather events in the studied area. To decide the direction, it is important to estimate the typical behavior of weathers in the region. The direction is random, each studied region has only a few possible directions (Θ) because severe weather originate in a particular area and usually follow one or two prevailing directions, for example from the ocean and in over land [10]. The wind part and the ice part of severe weather may have different sizes, moving speed and direction.

4 MODEL OF COMPONENT VULNERABILITY

Assuming that the load functions for each segment are known, how probable is it that a segment break down? The extent to which a segment is affected depends on severity, direction and moving speed of the weather. However, the way in which a segment is affected is also heavily dependent on the design of network components and their condition at the time of the storm (i.e. initial damage due to corrosion, etc) [7]. Since it would be impossible to consider the status of every component in the network it is assumed that the probability of an individual segment breaking down under impact of a given weather depends on the load function together with the component vulnerability model.

A given *weather* will give a certain *load* on the components. Depending on the *vulnerability* of the components it will take different times until the component *breaks*. Both the weather, loading vulnerability and time to break are in reality stochastic. We have chosen to treat only the vulnerability as stochastic, and the weather, the load and the threshold breaking as deterministic. A stochastic behavior of a given weather and a deterministic model for component vulnerability can be replaced by a given weather's deterministic properties and a stochastic impact on towers.

The stress on a segment due to wind increase with increasing severity level. The stress due to ice depends on the accumulated weight of ice, the risk of failure depends both on how long the ice has been there and its weight. As long as the ice is built up the stress will increase, then the stress level will be constant since the melting process is neglected. It is assumed that no break downs will occur when the ice load function is constant, that is after t^{stop}.

In the vulnerability model, different stress levels correspond to different failure rates, λ [number of breakdowns/(h, km)]. λ is a continuous function of the load, which in turn is a function of time since the weather is moving.

$$\lambda_W(t) = f(L_W(t)) \tag{7}$$
$$\lambda_I(t) = f(L_I(t)) \tag{8}$$

λ is also dependent on design criteria, or design load (dl), of the considered tower.

In order to treat the risk of failure of the transmission line, we have selected the exponential distribution of the time to failure. This means that the process is assumed to have "no memory". But to include the changed risk of failure because of changed amount of wind and ice load, the parameters of the distribution is controlled instead in order to obtain a realistic behavior of the connection between the loading and the risk of failure. In this way we can control the process more directly. It is of course possible to select another type of process that includes a "memory" in order to include the possible fact that the risk of failure might increase also if the loading is constant depending on fatigue. This may be a future extension if it is possible to obtain information about possible parameters. Let the stochastic variable be *time to failure. Expected time to failure* is the parameter m in the exponential distribution.

$$m(t) = \frac{1}{\lambda(t)}, \tag{9}$$

The probability density function for the exponential distribution with parameter $m(t)$ is

$$f_T(t) = \begin{cases} \frac{1}{m(t)} e^{-\frac{t}{m(t)}} & \text{if } t \geq 0 \\ 0 & \text{otherwise.} \end{cases} \tag{10}$$

The probability of break down of a segment in the time interval $[t, t + \Delta t]$ is analytically given by

$$P(\text{failure in interval } [t, t + \Delta t]) = \int_t^{t+\Delta t} f_T(u)du. \tag{11}$$

which can be approximated with $f_T(t)\Delta t$ if $\Delta t \to 0$.

Assume $\lambda(t)$ due to wind and ice are known, then the probability of breakdown in the time interval $[t, t + \Delta t]$ in each segment is known by equation (11) or its approximation. The total probability density function is given by weighing the failure rates for break down due to ice and wind together, with weights a_W and a_I.

$$\lambda = a_W \lambda_W + a_I \lambda_I. \tag{12}$$

The probability of break down therefore consists of a direct factor and an integrating factor. The direct factor corresponds to the probability of break down due to the wind load. The integrating factor corresponds to ice load and is needed because the line has been affected earlier and is under stress.

The time for a possibly break down can be calculated for each simulation by deciding stochastically whether a break down occur or not for each t until the first break down or time reaches t^{stop}. Monte Carlo techniques can be used to calculate the distribution of time to failure for different segments and lines.

The condition of adjacent segments are likely to affect the segment, this is important for an estimation of repair times. The dependence of segment failures it is not included in this paper since break down of one segment is enough for a line break. Weather events such as lightnings are not considered either, since a transmission network is dimensioned for lightnings and they normally do not cause as large damages as ice storms.

5 NUMERICAL EXAMPLE

A transmission network typically covers large areas and meets different weather conditions due to geographic differences. In this example non-dimensioning stresses on the network and their consequences on components in the area of interest are studied. Area of interest is a transmission network consisting of three lines which are studied when exposed to an ice storm. The aim is to investigate the persistency to ice and wind of the different connections in the studied network. A scheme of the network is shown in figure 8, the lines and segments are numbered according to the figure.

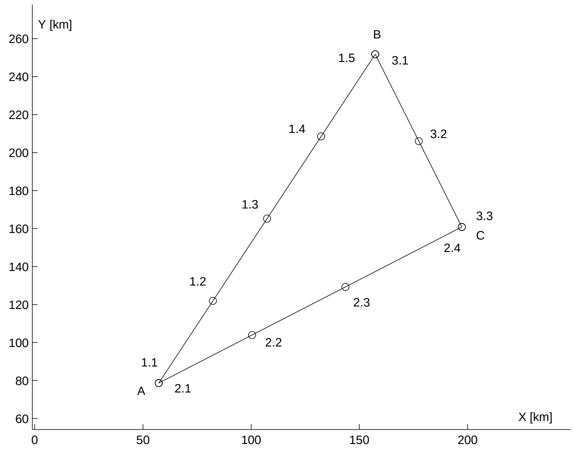


Figure 8: Th e network studied in the numerical example

In each simulation the ice storm hits the network with same strength and same angel, i.e V_h and Θ are constant for both wind and ice. Thus the ice and wind load are the same for a specific segment during all simulations. However, the influence on the lines will vary because of the stochastic nature of the vulnerability model. The ice part and the wind part has the same moving speed and the same angle, but the radius for the ice (R_{ice}) is smaller than the radius for wind (R_{wind}). If a segment break down under influence of the ice storm the whole line becomes out of function. Only the time for the break of the first segment that breaks down on each line is registered. A segment is represented by a point with coordinates (x, y). The properties of a stochastic weather can be chosen as in section 3.5. In this numerical example the failure rates are chosen equal for all segments, it would though be possible to have different failure rates for segments placed on different grounds, for example in the forest or on an open field. Data are from ice storm events in Sweden and Canada, see section 5.2.

5.1 Calculations

The number of scenarios, n, is 1000 in this example. To achieve convergence in simulations n=800 is enough, the result differs on the third decimal from the case when n=1000, but the number of scenarios should not be chosen less than 600. The weather parameters are chosen identically for each simulation. The wind and ice load function for each segment are calculated according to (3) and (5).

The λ-function is an increasing function of wind force and ice loading, see tables 1 and 2. The total failure rate is calculated as in equation (12), with $a_W = 0.1$ and $a_I = 0.9$. These weights are an important but difficult issue. To get a clue of the ratio we have been in contact with industries and they have agreed on that $a_W = 0.1$ and $a_I = 0.9$ is a good choice for this first approach.

Equation (11) is used to get the probability for breakdown in each segment at each time step. A time step is 36 s or 0.01 h. For each simulation it is decided whether a break down occur or not for each segment and time step, stopping at the time when a breakdown occur or when the weather has passed, i.e time exceeds t^{stop} for that particular segment. If the probability of break down at time t exceeds a random number from a uniform distribution, U(0,1), a break down is registered for the studied segment.

The 1000 simulations takes less than three minutes to simulate in matlab on a Pentium 4, 2.80 GHz, 512 MB computer. The number of segments can be increased easily but that will affect the simulation time, a larger time step can be chosen when many segments are studied.

5.2 Data

Length of lines are 200 km, 162 km and 100 km divided into segments of 50 km. The maximum ice loading is 2 mm/h and maximum wind force is 36 m/s [12]. $R_{wind} = 200$ km and $R_{ice} = 130$ km is (with k=30, see section 3.3). σ_x and σ_y are chosen according to equation (13).

$$\sigma_x = \sigma_y = 0.4R \text{ for } R = R_{wind} \text{ and } R = R_{ice} \qquad (13)$$

The towers are assumed to be designed for a wind load of 40 m/s. Canadian standard for only ice is 5 cm [11]. This standard demands a large and long lasting severe weather for an extensive damage on the network. To make this example illustrative we have chosen to study more vulnerable components.

λ_W and λ_I are defined as in tables 1 and 2 where dl is design load.

L_W	λ_W $[\frac{1}{h,50km}]$
$L_W \leq 0.9 \cdot dl$	$1.2 \cdot 10^{-5}$
$0.9 \cdot dl < L_W \leq 1 \cdot dl$	$8.0 \cdot 10^{-4}$
$1 \cdot dl < L_W \leq 1.1 \cdot dl$	0.048
$1.1 \cdot dl < L_W \leq 1.2 \cdot dl$	0.060
$1.2 \cdot dl < L_W \leq 1.5 \cdot dl$	0.028
$1.5 \cdot dl < L_W$	0.04

Table 1: λ_W as a function of wind load

L_I	λ_I $[\frac{1}{h,50km}]$
$L_I \leq 0.3 \cdot dl$	0
$0.3 \cdot dl < L_I \leq 0.5 \cdot dl$	$4.5 \cdot 10^{-3}$
$0.5 \cdot dl < L_I \leq 0.9 \cdot dl$	0.010
$0.9 \cdot dl < L_I \leq 1 \cdot dl$	0.015
$1 \cdot dl < L_I \leq 1.1 \cdot dl$	0.033
$1.1 \cdot dl < L_I \leq 1.2 \cdot dl$	0.050
$1.2 \cdot dl < L_I \leq 1.5 \cdot dl$	0.071
$1.5 \cdot dl < L_I$	0.10

Table 2: λ_I as a function of ice load

λ_W and λ_I are chosen such that the impact of wind is approximately 10% and the impact of ice is approximately 90%. $\lambda = 1.2 \cdot 10^{-5}$ means that the tower breaks down every tenth year, $\lambda = 0.1$ means that the tower breaks down 0.1 times every hour or every tenth hour. The size of time step is included in the choice of λ, otherwise would a smaller time step give a more vulnerable segment. A smaller time step with a factor c means that the size of λ should be decreased with the same factor. Direction for both wind and ice are $\Theta = 0$ which with $\mu_x(0) = 0$ and $\mu_y(0) = 140$ gives

$$\begin{aligned} \mu_x(t) &= 90t \\ \mu_y(t) &= 140. \end{aligned} \qquad (14)$$

according to equation (6). The weathers move 0.9 km in x-direction for each time step and 0 km in y-direction, i.e $V_h = 25m/s$ with a time step of 0.01. The centre i located in $(90t, 140)$.

The ice load function is symmetric and the wind load function is of the type in figure 3.

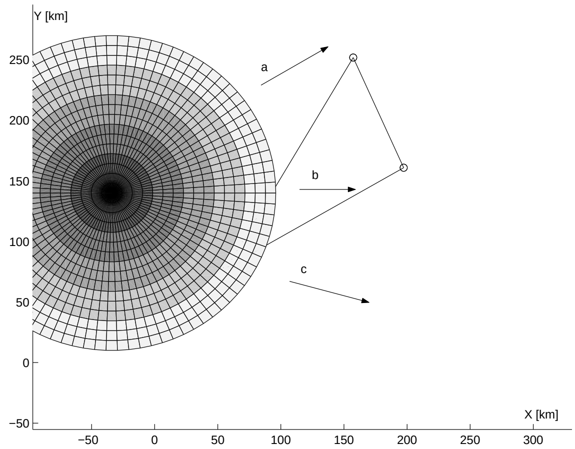


Figure 9: The weather in the example moves in direction b.

6 RESULTS

Table 3 shows the result of the first ten simulations.

sim.	A-B		A-C		B-C	
	time	seg.	time	seg.	time	seg.
1	-	-	3.33	2.3	-	-
2	5.64	1.3	4.18	2.2	-	-
3	-	-	-	-	-	-
4	-	-	-	-	-	-
5	4.36	1.2	5.21	2.3	-	-
6	2.48	1.4	4.43	2.2	2.89	3.3
7	-	-	-	-	-	-
8	-	-	-	-	-	-
9	4.94	1.4	-	-	4.35	3.3
10	2.67	1.3	4.27	2.2	-	-

Table 3: Times for breakdown and segment number

A break down at time 5.64 means break down 5.64 hours after the weather's centre has left $(0, 140)$ in figure 8. Connection A-B broke down in 51.2% of the 1000 simulations, connection A-C in 56.0%, and connection B-C in 26.1%. It is clear that connection B-C is the most persistent to the simulated storm. Connection B-C is affected a shorter time period and is hit by almost parallel wind in larger extent than connection A-B and A-C. A shift of the direction of the weather has large impact of the result. It is not often more than one segment of a connection break down in the same simulation. A long line with many segments is more vulnerable, since break down in one of the segments is enough for a total break down.

The ice storm impact can be divided into 8 cases, listed in table 4 together with their probability.

case	event	probability
1	no bd	16.3%
2	b.d. in A-B	16.1%
3	b.d. in A-C	20.0%
4	b.d. in B-C	5.1%
5	b.d. in A-B and A-C	21.5%
6	b.d. in A-B and B-C	6.5%
7	b.d. in A-C and B-C	7.4%
8	b.d. in all connections	7.1%

Table 4: b.d. = break down

Note that if connections A-B and A-C are functioning there is a connection between B and C, even though line B-C is out of order. There is a connection between B and C in $16.3\% + 16.1\% + 20.0\% + 5.1\% + 21.5\% = 79.0\%$ of the simulations. Connection between A-B in 64.9% and connection between A-C in 64.0% of the simulations.

7 CONCLUSIONS

This paper has described a new technique of modelling adverse weather. The risk for outage due to direct wind impact and integrating impact of ice loading in particular lines has been calculated for a numerical example. Furthermore are the times for break down of the different line segments calculated, and thereby can the time differences between outages in different lines be estimated.

REFERENCES

[1] *Security in a new time*, SOU 2001:41, only availiable in Swedish.

[2] G. Fischer and S. Molin, *The Ice-Storm in Canada*, FOI- Swedish Defence Research Agency,FOI-R–0101-SE, May 2001, only avaliable in Swedish

[3] R. Billinton and R. N. Allan, *Reliability evaluation of power systems*, Plenum Press, 1984

[4] M. R. Bhuiyan and R. N. Allan, *Inclusion of weather effects in composite system reliability evaluation using sequential simulation*, IEE Proc. -Gener. Transm. Distrib., Vol 141, No 6, November 1994

[5] Tom B. Gutwin, *Application of BCTC Standardized Risk Estimation Model to Assess Risk Due to Ice Storms*, PMAPS, Iowa State University, Ames, 2004

[6] M. Bourdages, *An experimental overhead disribution line for ice loading rupture tests*, CIRED 2004

[7] Ibrahim Hathout, *Damage Assessment and Soft Reliability Evaluation of Existing Transmission Lines*, PMAPS, Iowa State University, Ames, 2004

[8] Communication with Hans Alexandersson at SMHI, Swedish Meteorological and Hydrological Institute

[9] Communication with Dr Gillies Sabourin, Hydro Quebec, Canada

[10] C. D. Ahrens, *Meteorology today: an introduction to weather, climate and the environment*, Pacific Grove Brooks/Cole, 2000

[11] Hydro One's Ice Storm (1998) report recieved from I. Hathout at Hydro One, Canada

[12] S. Lindström, J. Martinsson and E. Sundin *Investigation of the October 1921 ice storm*, SwedPower, 2001, only availiable in Swedish.