Ice Storm Impact on Power System Reliability

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***Abstract*— Ice storms are freezing rain that coats everything in ice, often in combination with heavy wind. The aim of the methods developed in this paper is to estimate the risk of failure due to ice storms. This includes a severe weather model, a new method for choosing weather parameters and a component vulnerability model. The weather model is based on how a low pressure behaves and consists of functions that describe the wind and precipitation parts of the weather. An ice accretion model is used to estimate the ice loads. The method for choosing weather parameters is useful for Monte Carlo simulations where the effects of many different weather situations are studied. In the stochastic component vulnerability model the failure rates are based on how an increased ice load influences the critical wind. Swedish weather conditions and transmission components are used in the case study and the loads and their impact are estimated for many different weather situations.**

I. Introduction

ELECTRIC power supplies are of particular importance for a modern society. Severe weather may lead to difficulties in maintaining power supplies for a long time. An ice storm is an extreme weather situation, which occurs very infrequently in most parts of the world but can cause extensive damage when it does. Ice storms occur when super cooled rain freezes in contact with trees or overhead lines and forms a layer of ice. Fig 1. shows towers exposed to icing.

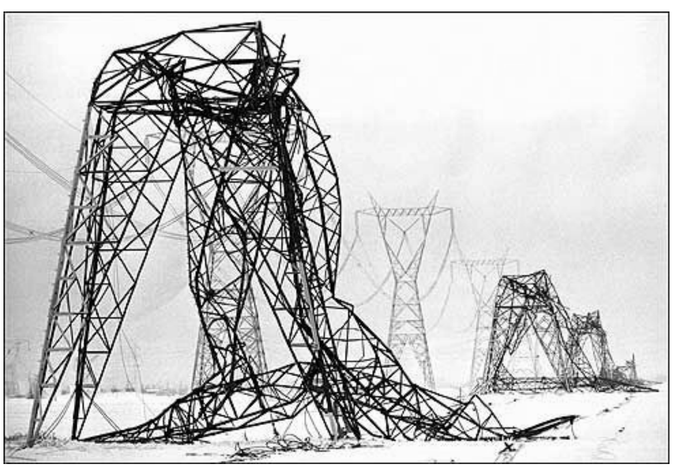

Fig. 1. Canadian towers that have failed due to icing during the 1998 storm.

The ice storm that hit eastern Canada and northeastern United States in January 1998 caused a crisis where about 1.5 million households were without electricity and the system was not completely restored until October 1998 [1], [2]. Another recent example is the ice storm that hit Germany in November 2005. More than 70 transmission towers were broken and 200 000 people were affected by the blackout [3]. There was an ice storm in Sweden 1921; since the society is much more dependent on the infrastructure now the consequences if this storm would have happened today are not comparable.

Methods for including the impact of weather on power system 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 for each situation [4]. The two-state and many other models assume the entire network to be in the same weather environment. In [5] is a wide range of weather severities considered instead, but the distribution of severity levels is discrete 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 [6]. The impact on the towers is assumed to be deterministic; the towers break down at a given ice load that is estimated based on experiments.

None of the papers described above considers the time dependent risk level on lines when a severe weather passes a region. A technique of modelling severe weather for power system reliability calculations is developed in [7] and improved in [8]. This technique considers the time dependent risk level will be briefly described in this paper. The weather model is suitable for both transmission and distribution networks and is based on geographically moving winds and ice storms. The modelled weather has severity levels for wind and ice that vary with time and changes continuously as the weather moves. A known ice accretion model is used to estimate the ice load.

The weather parameters, such as size, strength, speed and direction can vary. A stochastic method for choosing parameters will also be described in this paper. To structure different types of weathers weather codes can be used, for example as in [9], where the wind gust speed is classified into three discrete intervals. Another approach is to study weather statistics for the studied area. However to achieve data from the most severe possible weathers the weather statistics for even a few hundred years is not enough, especially if the weather conditions will become more extreme in the future. Instead well-documented weather situations can be modified based on estimations of frequency of situations with increased precipitation and wind, and estimations of the probability for a change in the weather conditions that would have lead to the more severe scenario. A common way to handle probability for different weather states is to use return periods for different weather conditions, for example wind speeds. It is then common to connect the weather states with a certain return period to different component failure rates. In [10] the variations of wind speeds with return periods of 5, 50 and 500 years are discussed. Two methods for modelling failure rates for overhead distribution lines during the different weather states represented by the weather codes are also presented in [9]. The first uses a Poisson model for failures to describe the probability of failures during different weather codes. The other method consists of a Bayesian network with nodes, which represent wind speed, lightning and number of events and is used together with a conditional probability table to map the relationship between the weathers and the failure rates. The method developed here does not directly connect a weather situation to a failure rate. Instead the method connects a forecast of a severe weather to distributions of weather parameters. This new method for randomly choosing weather parameters of the possible weathers can be used to simulate different weather scenarios, which in combination with the weather model give the loads on components. Thereafter are the loads connected to different failure rates by a vulnerability model for components. In the component vulnerability model used and briefly described in this paper the loads are compared to the critical wind and ice loads for the studied lines. Details of this model for the impact of the simulated weather on transmission lines can be found in [8] and [11].

The risks of power outages in connection to weather situations can be analyzed given the structure of the transmission and distribution networks in the area. Monte Carlo methods, where many different weather situations are simulated, are used in the case study where the system vulnerability is studied for a small fictive network. The probabilities for outage in different load points are estimated.

II. The Weather Model

The model consists of one function that describes the wind part of the weather and another function that describes the precipitation part of the weather. The precipitation can be assumed to fall as freezing rain and an ice accretion model is used to estimate the accreted ice on components. The accreted ice gives the time dependent *ice load function* for each component. The impact of the wind is direct and the time dependent *wind load function* is the perpendicular component of the time dependent *wind function* that describes the wind part of the weather. Sizes, intensities, moving speeds and directions of the possible weathers are easily changed within the proposed model. *The moving speed* describes how fast the weather is moving through the exposed area. The weather is moving according to functions for how the centers of the wind part and the ice part are moving. The details of weather model illustrated here is based on Swedish conditions but can be adjusted to be valid for other countries also.

A. Wind load

The impact of the angle by which the wind hits the power line is considered in the model and perpendicular wind is the worst case. The wind is often stronger south and west of the center of the low pressure and the wind can be assumed to have its maximum 300 *km* approximately southwest from the center at least in Sweden [12]. R_{wind} is the radius of the wind area. Θ is the angle to the x-axis. The amplitude A_W [*m/s*] refers to the maximum wind 300 *km* away from the center with Θ=240°. The wind part of the weather has for one choice of parameters the shape shown in Fig. 2. Details of the wind load function can be found in [8].

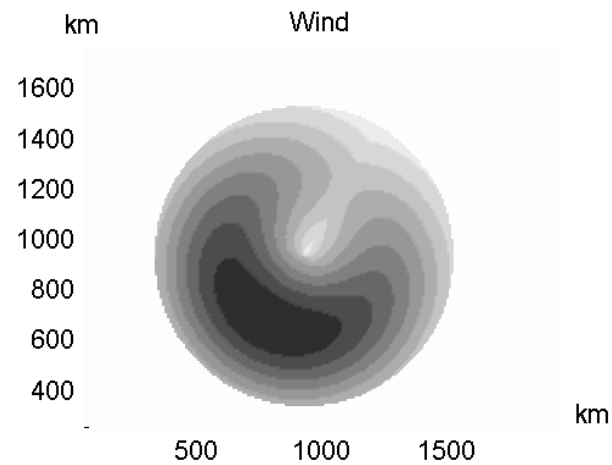

Fig. 2. The shape of the wind part of the weather model. The grey scale represent the intensities of the wind which are largest 300 km southwest of the center (A_W=38 m/s). The center is at this moment located at (1000,1000).

B. Precipitation

The precipitation area is modelled in two parts. Close to the center of the low pressure the precipitation area can be assumed circular and the most intensive precipitation is found close to the center of the low pressure [13], [14]. This is modelled with one function that gives the largest values in the center and decreases with the radius, R_{ice}. The constant A_I is the precipitation rate in the center. A front zone often follows the precipitation area around the center. The front zone precipitation is modelled with largest intensity close to the center area; the intensity decreases with the distance from the center of the circle. The width of the front is dependent on the radius of circular part of the low pressure. The functions for the precipitation part of the weather are described in detail in [8] and [11]. The shape of the precipitation part of the weather shown in Fig. 3 is similar to the shape of a low pressure in its most violent phase [13].

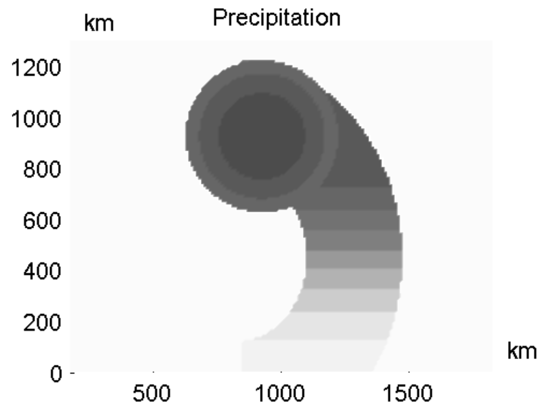

Fig. 3. The shape of the precipitation part of the weather. The intensity is decreasing from the center of the circular part and A_I =10 mm/h.

C. *Ice accretion*

The ice load function is the accreted ice given by an ice accretion model. There are many models for deposition of freezing rain and wet snow on objects. *The Simple model* [15] uses parameters that are given by the weather model described in this paper, for example the precipitation rate. However it is necessary to assume the size of the droplets. It can be assumed that all the droplets that hit the surface of the line freeze. This means that no icicles are developed. Among other ice accretion models the Simple model assumes a perfect circular shape; this is reasonable because of the power lines ability to rotate.

Ice accretion is dependent on the wind and this is also included in the Simple model. The perpendicular component of the mean wind, V_{mean}, is used to calculate how much ice that is deposited on the lines. The gust wind is given by the weather model and the relation between V_{mean} and the gust or maximal wind, V_{max}, can be approximated by $V_{mean} = k_g V_{max}$. The factor k_g differs for different storms and for different types of terrain. k_g=0.7 is used in the investigation of the Swedish ice storm 1921 [16] and in the case study in this paper. In [17] is V_{mean} =0.73 V_{max}, 25 *m* above sea level.

III. Method for Choosing Parameters for Monte Carlo Simulations

The weather parameters can be chosen from their distributions according to the method described in this section. The method described here focuses on parameters for simulations of severe weathers and thereby the probability for an outage given a severe weather forecast can be estimated. Another approach is to estimate the probability of outages by simulate all possible weathers. The approach is given by the choice of weather codes in section *B*. It is also possible to simulate the same weather with identical parameters in all simulations. The impact on the network will vary between different scenarios because of the stochastic nature of the component vulnerability model.

The different weather and simulation parameters are as in table I. The choice of Δt influences the simulation time.

TABLE I
Modelling Parameters

Δt	Length of time step
(x_{start}, y_{start})_	Start position of weather
R_{wind}	Radius of wind area
R_{ice}	Radius of precipitation area
Θ	Direction of weather
V_h	Weather moving speed
A_W	Maximal intensity of wind
A_I	Maximal intensity of ice

A. *Main direction of weather*

To estimate the distributions of possible directions it is important to consider the possible behaviors of weathers in the region. Each studied region has a few directions that are more likely than others, because severe weather originates in a particular area and usually follow one or two prevailing directions, for example from the ocean and in over land [18].

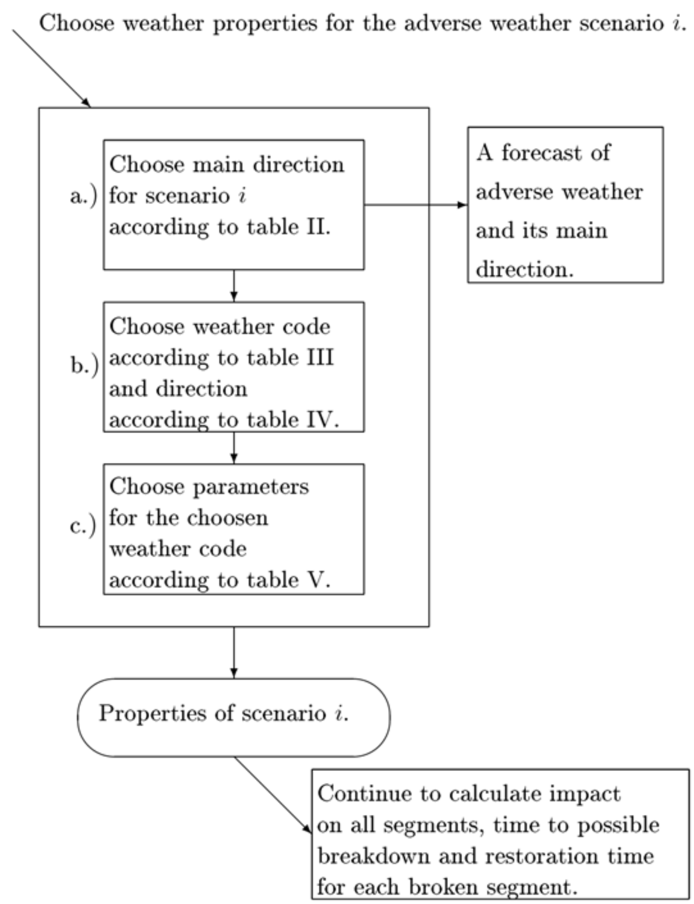

Fig. 4. Flow chart of method for choosing weather properties for Monte Carlo Simulations.

To include the small probability that a severe weather originates from another direction than the most common ones the *main direction* of the weather is specified according to table II.

TABLE II
Probabilities for different main directions of the severe weather

Main direction	Probability
The most common direction	p_{common}
All other directions	1- p_{common}

The flow chart in Fig. 4 shows the stochastic method for choosing weather parameters for a severe weather scenario.

In each scenario the main direction is chosen by generation of a uniform random number between 0 and 1. If the random number is smaller than p_{common}, *the most common direction* is chosen for this particular scenario, else is *all other directions* chosen. This is box *a* in Fig. 4.

B. *Weather code and direction*

Severe weather is here defined as wind forces above 25 m/s or that ice builds up on the lines, or a combination. These cases are listed in table III and are represented by a weather code for simplicity. The approach is to assume that a forecast of a coming severe weather is available including assumptions of the probabilities for the different scenarios listed in table III. The sum of p_1, p_2 and p_3 is always one. These probabilities vary for different weather regions but are difficult to estimate and this estimation is even more difficult for future weather conditions. In each scenario the weather code is chosen in relation to the estimated probabilities. This is the first part of box *b* in Fig. 4.

TABLE III
DEFINITION OF WEATHER CODES AND THEIR PROBABILITIES

Weather code	Condition	Probability
1	No ice but wind >25 m/s	p_1
2	Ice and wind <25 m/s	p_2
3	Ice and wind >25 m/s	p_3

After choosing whether the main direction is the *most common* or *all other directions* there is a forecast of a weather that will be severe according to one of the definitions in table III and its main direction is known. Here a forecast means what usually is known by meteorologists a few days before a severe weather hits the region for example that a severe weather is coming and from which main direction [19]. Since it is not unusual for the wind direction to change during a storm [18] the distribution of Θ is chosen after the forecast with warnings of severe weather and where it comes from is given. This is the second part of box *b*. Θ is independent of weather code, but depended on main direction and is here assumed uniformly distributed. The uniform distributions in table IV is for Swedish case studies where the most common direction south-west-west or $-45°\leq\Theta<45°$. Other distributions of the direction are possible, for example the Gaussian distribution. The start position, (x_{start}, y_{start}), for the center of the weather depends on main direction.

TABLE IV
THE DISTRIBUTION OF DIRECTIONS FOR LOW PRESSURES IN SWEDEN, GIVEN THE MAIN DIRECTION.

Main direction	Θ
The most common direction	U(-45°,45°)
All other directions	U(45° ,-135°)

C. *Size, intensity and moving speed*

The other scenario parameters needed in the weather model, see table I, are: maximal wind force, A_W; radius of the wind area, R_{wind}; the radius of the circular part of the precipitation part of the weather, R_{ice}; the maximal intensity in the circular part, A_I; the weather moving speed, V_h . The maximal intensity in the front zone, A_{I_front}, is always smaller than A_I by the weather model. Choosing these parameters corresponds to box *c* in Fig. 4. The wind part and the ice part of severe weather may have different sizes and the ice part of the weather is typically smaller than the wind weather. R_{wind} and R_{ice} are here assumed uniformly distributed within a suitable range for each weather code, see table V. The distributions shown in table V are the distributions used in the case study.

The distributions of the intensity of precipitation and the maximal wind speed have to be estimated for each weather code and are assumed to be Gaussian distributions. For weather code 1 there is no icing and the maximal precipitation rate is zero since no other precipitation than freezing precipitation is considered in the weather model or the vulnerability model for components. Weather code 2 and 3 include precipitation rates and the precipitation is supposed to fall as freezing rain.

It is difficult to forecast how fast a low pressure will move. Some low pressures move very fast and others move slowly and they can even be stationary. There is no obvious correlation between how fast a low pressure moves and how severe it is [18]. The moving speed is independent of weather code since it is not connected to the strength of the weather, see table V, and it is here assumed Gaussian distributed.

None of the Gaussian distributed parameters in table V allow negative numbers and therefore a minimum possible value has to be used to avoid unrealistic weather parameters. A maximal value can also be useful for example to only achieve realistic wind speeds and wind speeds within the interval of a certain weather code.

TABLE V
DISTRIBUTION OF WEATHER PARAMETERS GIVEN WEATHER CODE

Weather code	R_{wind}	R_{ice}
1	U(300,900)	0
2	U(400,800)	U(50,500)
3	U(300,900)	U(50,50)
Weather code	A_W	A_I
1	N(35,15) Min 25, Max 60	0
2	N(5,5) Min 0, Max 10	N(8,5) Min 0, Max 15
3	N(38,20) Min 10, Max 60	N(8,5) Min 0, Max 15
Weather code	V_h	
1, 2, 3	N(16,15) Min 10, Max 50	

IV. Component Vulnerability Model

To be able to connect the risk of transmission outage to the weather situation, a vulnerability model for the components is required. Because of the complexity of modelling the influence of severe weather, the network components such as line segments and towers are 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. Each segment is exposed to certain load functions. The segments may break down under influence of the severe weather, i.e. the wind load function and the ice load function. A single segment breakdown is enough for the whole line to become disconnected, but the system restoration time increases if more segments fail. Assuming that the load functions for each segment are known, how probable is it that a segment breaks down?

The vulnerability model is stochastic and based on the design of the components. Different stress levels correspond to different failure rates, λ [number of breakdowns/(h, km)].

λ is a continuous function of the loads, which in turn are functions of time since the weather is moving. To include the changed risk of failure because of changed amount of wind and ice load, the parameters are controlled in order to obtain a realistic behavior of the connection between the load and the risk of failure. A time dependent distribution of the time to failure is chosen, it is the exponential distribution with time dependent parameters; see more details in [11].

The parameter $\lambda(t)$ is failure rate, which changes with time, t. The probability density function is:

$$f(t) = \begin{cases} \lambda(t)e^{-\lambda(t)t} & if\ t > 0, \\ 0 & otherwise. \end{cases} \quad (1)$$

The probability of breakdown of a segment in time interval $t+\Delta t$ is given by:

P(*breakdown in interval* [t, t+Δt]) =

$$= \int_t^{t+\Delta t} f_T(u)du \approx f_T(t+\frac{\Delta t}{2})\Delta t \text{ if } \Delta t \to 0 . \quad (2)$$

Assume that $\lambda(t)$ is known; then the probability of breakdown in the time interval $[t,t+\Delta t]$ in each segment is known by (2). Given the failure rates by a vulnerability model, for example the one first described in [20] and briefly in this section the approximation in equation (2) is used to get the probability for breakdown in each segment at each time step. The time for a possible breakdown can be calculated for each scenario simulation by deciding stochastically whether a breakdown occurs or not for each time step until the first break down.

The ice and wind loads are varied in the scenarios and knowledge of how an increased ice load influences the critical gust wind is necessary to calculate the failure rates for different loads. An example of the described component vulnerability model is shown in Fig. 5. The different areas 1-4 in Fig. 5 corresponds to different failure rates. The failure rates used in this case study are listed in table VI. Data is from the Swedish transmission system operator Svenska Kraftnät and Vattenfall power consultants have performed a detailed calculation on when the first tower break down at different ice and wind loads for both lines.

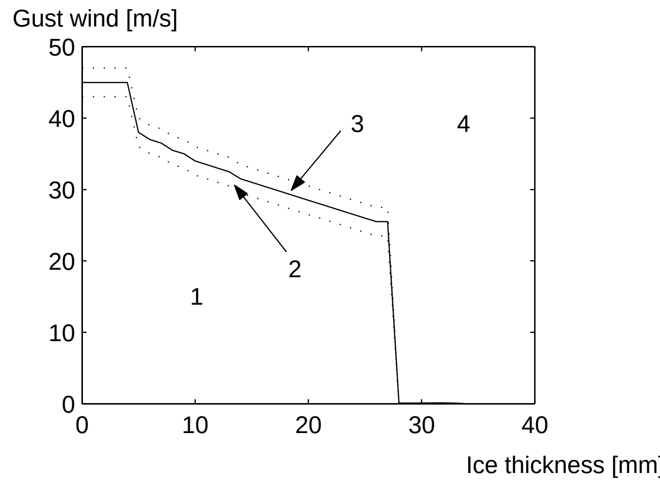

Fig. 5. Critical loads for one of the studied power lines.

When the ice thickness exceeds about 28 *mm* on the power line the weakest towers break due to the ice load alone. The loads in area 1, see Fig. 5, are not enough for causing breakdowns. See table VI for the failure rates in the other areas of Fig. 5. which are used as a stochastic model of segment vulnerability in the numerical examples.

TABLE VI
Failure rates for the different areas in Fig. 5.

Area	1	2	3	4
λ	0	0.2	0.5	1

The failure rate functions are here 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 and different failure rate for segment with different initial condition e.g. corrosion.

V. Case study: Distributions of weather parameters and power system reliably

The case study shows the risk of outage in different load points as well as the impact of the different weather situations on the components and is based on distributions and probabilities that are assumed to be valid for Swedish conditions. The approach is to estimate the reliability of components using Monte Carlo simulations. The method for choosing different weather parameters for each scenario is used together with the weather model and the component vulnerability model on a fictive network.

p_{common} was assumed to be 0.8 and p_1, p_2 and p_3 were assumed to be 0.85, 0.1, 0.05 respectively. Tables IV and V show which distributions are used in this case study. Most low pressure systems that reach Sweden develops on the North Atlantic and moves towards the northeast over Scandinavia. This direction is used as the main direction in the simulations for Sweden. Θ is assumed to be the same for the wind and ice parts of the weather in the case studies.

The precipitation rates, where the maximal precipitation rate is from distributions in table V, give precipitation and ice load for the 138 out of 1000 simulations that gave non-zero freezing precipitation. Only a few of these cases lead to ice formation on the studied power lines since the direction of the weather varies. The moving speeds of the wind and precipitation part of the weather are assumed to be the same in the case studies.

1000 simulations of different weather situations are performed on the network in Fig. 6.

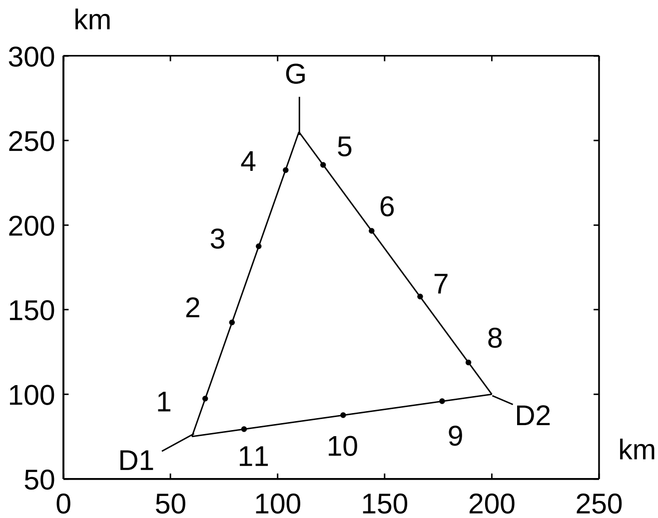

Fig. 6. The studied network with generation point (G) and load points D1 and D2.

A longer line is more vulnerable than a shorter line that consists of fewer segments. To be able to compare outage times for load points D1 and D2 the network is almost symmetric around the generation point.

The broken segments are identified and the times for breakdown are estimated. To be able to estimate the system reliability, the distribution of outage times for the load points D1 and D2 can be estimated. However the probabilities for outages in the load points are low; 0.2 % of the scenarios lead to an outage at load point D1 and 0.3 % lead to an outage at load point D2, it is thus difficult to estimate the distribution without using variance reduction techniques for choosing interesting weather situations for studies. There is an outage in D1 if one or more of segments 1 to 4 and one or more of the segments 5 to 11 are broken. There is an outage in D2 if one or more of segments 5 to 8 and one or more of the segments 1-4, 9-11 are broken.

VI. Conclusions

The contributions of the paper are; a method for choosing weather parameter for modeling severe weather and their impact on transmission components using a weather model and a model for the impact on towers and line segments.

The case study illustrates the failure risk for particular line segments and disconnections of lines and the risk for outages in load points in a small meshed system. Different weather situations generated by the weather models were simulated. It has been difficult to find simulation data, both regarding the stochastic nature of the components and regarding distributions of possible weather parameters.

VII. Acknowledgment

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