Modelling of Ice Storms and their Impact on a part of the Swedish Transmission Network

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Abstract

In this master thesis a weather model to simulate an ice storm is developed. Precipitation, wind and movement are modelled by mathematical functions to create a realistic model.
The weather model is used to calculate wind and ice loads on power lines. Two different models for the ice accretion on the power lines are used and compared. Data from two storms in Sweden in 1995 and 1999 are studied. In the simulations, the precipitation is assumed to fall as freezing rain instead of snow. The ice and wind loads are calculated in detail for two power lines in southern Sweden. The calculated loads are compared to what is assumed to be the critical loads for the poles, and the risks of power outages in connection with these storms are discussed.

Acknowledgments

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Contents

Chapter 1

Introduction

Within the research project *"Reliability of the power system under severe crises in the boundary between market and essential Infrastructure"* among other things, the effects on the Swedish Transmission Network in adverse weather conditions are studied. Special attention is given to so called ice storms. In most parts of the world, this is a relatively rare weather phenomenon, with strong winds and freezing precipitation, which can be devastating for a power line.

During the last century Sweden has once been struck by such a heavy ice storm with very extensive damages to the transmission network in the southern parts of Sweden. This occurred in 1921 and it may be very difficult to draw any conclusions from what happened then to what might happen to today's transmission network. On a few other occasions Sweden has seen weather situations like the 1921-storm, although not as severe, and they have not caused as much damage. For example the southern parts of Sweden was hit in November 1968.

Maybe the most well known ice storm took place in Canada in 1998 [1]. During a couple of days heavy freezing rain and strong winds paralysed an area south of Quebec[2]. The power lines were completely destroyed and some areas suffered from power outages for weeks.

During an ice storm rain falls and as soon as it hits an object (for example a power line) it freezes. An ice layer builds on lines and poles. The added weight and added surface exposed to the wind makes the risk for the poles to break larger. Also short circuits may occur in connection with heavy icing.

An interruption in the power supply can cause major problems in today's society. Both industry and households are in great need of electricity, and they have a confidence in the power supply. Therefore it is of utmost importance to study any situation that can lead to a power failure and if possible prevent it.

In a research article E Broström and L Söder [3] has presented a weather model of an ice storm used for power transmission reliability calculations. A storm is modelled and hits a power line. Another model is used to see how much ice that is accreted on the power line. An estimation of the failure rates as a function of the ice and wind loads is made to calculate the risks of a power failure.

In this master thesis a more advanced model to simulate an ice storm has been developed. The basic idea is the same, but the geometric shape of the precipitation area has been more carefully studied, and as a result further developed. Some changes have also been made to the wind area to obtain an even better model of an ice storm.

Two different models for the ice accretion on the power lines are used and compared. These models makes it possible for us to draw more accurate conclusions on how much snow and ice that is accreted on a power line than in the Broström Söder research article [3].
Two authentic storms from 1995 and 1999 have been slightly modified and the effects of the modified storms have been studied. The effects on a part of the Swedish Transmission Network is also studied. Detailed calculations have been performed to calculate the number of poles breaking down in a specific weather situation. Conclusions from these calculations can be drawn to a wider range of weather situations.

Chapter 2

Weather conditions in cyclones

Most of the precipitation in Scandinavia in the autumn and winter comes from low pressures created over the North Atlantic. Some of them deepens and turn into severe storms. These low pressures are often called cyclones [4].

The cyclone develops its characteristics within 24 hours and a low pressure center emerges. There are also two fronts; one warm front and one cold front. The fronts move along with the center and are in the beginning separated from each other. See figure 3.4(a). As the weather gets more severe the pressure in the center falls and the precipitation area grows. The cold front moves faster than the warm front and as time goes on it will occlude[1] with the warm front. See figure 3.4(d).

On the north side of the globe the wind blows anticlockwise around the center of the cyclone and the wind is often stronger south and west to the center (Behind the low pressure). This means that the strongest winds often blows from the west or north-west.

The precipitation is associated to the two fronts and around the center. In connection to the warm front the most common form of precipitation is not very intensive but has a rather long duration. Close to the cold front the precipitation is more intense but more in the form of showers. The most intensive and longest lasting precipitation is found close to the center [4].

The cyclone moves along with the airflow high up in the atmosphere and the movement often slows down as the cyclone matures.

The shape of the area of the precipitation is changing during the lifetime of a cyclone. That is an effect of the cold front moving faster than the warm front and after a while occlude, at least close to the center. That gives a problem of how to model the precipitation area.

Freezing rain is most often associated with the passage of the warm front. The air is much colder in the lower air layers of the atmosphere than it is in the higher. As a result the rain freezes as it falls. However; this kind of precipitation is often rather light and has a rather short duration, really heavy fall of freezing rain, as we are interested in modelling, is a very special phenomenon and can not be said to be specifically associated with the warm front. Freezing rain is most

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[1] Meteorologic term for the fusion of the warm and cold fronts

often observed when the temperature close to the ground is just below zero. The precipitation, falling as snow, first melts to water when it is warmed up in a layer with warmer air. Lower down to the ground the temperature is below zero and the water freezes as soon as it touches an object. Normally the precipitation rate in these situations is rather small, up to 1 mm/h. Sometimes, however, very special situations occur and heavier freezing rain falls. These extreme situations are analyzed and simulated in this project.

It is very common that wet snow also falls in these situations as the warmer air breaks through. These snow fall are often connected to deep cyclones and the wind can also blow strongly. It happens quite often that one deep cyclone is followed by another. Most of the time the second is located a little bit more to the south [4]. The combination of the two weather systems can be devastating for the transmission network. Especially if the first one brings a lot of freezing rain and wet snow and the second has very strong winds blowing.

Chapter 3

General cyclone model

Based on our knowledge of how a cyclone is created and how it behaves during its lifetime we have developed a model of a severe cyclone. The model consists of two parts. One area of precipitation and one area of wind. In the model one function gives the values of the precipitation and another function gives the values for the wind. The precipitation rates are at its largest values close to the center of the low pressure and the strongest winds are blowing south-east to the center. The whole weather system is moving with speed v. Most cyclones are developed on the North Atlantic and moves towards the north-east in over Scandinavia. We have chosen this direction of movement in our simulations for Sweden. In the general weather model developed, these parameters are easily changed.

3.1 Wind

As mentioned in the last section the wind normally blows much stronger south and west to the low pressures center. Likewise, the strongest winds are not found in the center but some distance away. A good approximation is that the strongest winds can be measured 300 km from the center [7]. The wind is a little weaker both closer to the center and further out. With these two things in mind, a function that gives us the maximum gust wind speeds in an area around the low pressure has been developed. In polar coordinates the function looks like

$$v(r,\theta) = Ae^{-\frac{1}{k}(B*(r-30)^2+C(min(\theta-\frac{4\pi}{3}+2\pi,2\pi-(\theta-\frac{4\pi}{3}+2\pi))^2} \tag{3.1}$$
$$\text{where } r < 60$$
$$0 < \theta < 2\pi$$

where $r(miles)^1$ is the distance to the center and θ is the angle measured from the x-axis. The origo is always in the center of the cyclone. The amplitude A refers to the maximum wind measured 300 km away from the center and at an angle of $\theta = \frac{4\pi}{3}$ to the x-axis.

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[1] Swedish miles = 10 km

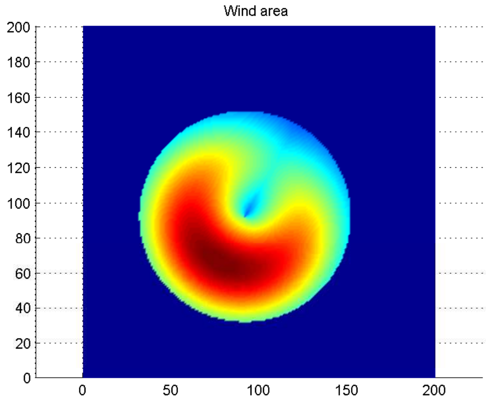


Figure 3.1: The modelled wind area

In Figure 3.1 the wind area is shown. The red color in the circle indicates strong winds and brighter color more moderate wind speeds.
The constants k, B and C are chosen so the appropriate decreasing of the wind speeds are found. For example are $k = 10000$, $B = 8$, $C = 30$ used in the Figure 3.1.
The wind speeds are discontinuous on the boundary between the area that has wind speeds greater than zero, and the surrounding, where the wind speeds are modelled to be zero. This is of course not a good simulation of reality, but the wind speeds are modelled to see how they effect the power line, and when the wind is very light, as it is close to the boundary, the effects on the power lines are negligible. Therefore this fairly bad approximation will not influence the results too much.

In the calculations of how much ice that is deposited on the wires the mean wind, M, is needed. The easiest way to get the mean wind from the maximal gust wind, G, is to multiply the maximal gust wind by a factor less than 1.

$$M = k_g G \tag{3.2}$$

There is no factor, k_g, that is generally accepted because it differs a lot from one storm to another. Likewise it differs a lot between different types of terrain. In the investigation of the ice storm in 1921 [10] the factor 0.7 was used in the northern parts of southern Sweden. For relatively open terrain the formula

$$k_g = \frac{1}{1 + \frac{2.28}{ln(\frac{h}{0.05})}} \tag{3.3}$$

where $h(m)$ is the height above the ground, is accepted [9]. With $h = 25\ m$ we get $k_g = 0.73$ which is very close to the 0.7 used in 1921 investigation [10]. We have chosen not to go to deep into this problem and have used $k_g = 0.7$ in our simulations.

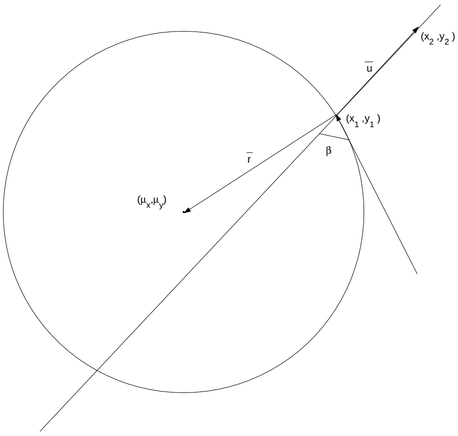


Figure 3.3: Calculation of wind direction

3.1.1 Wind direction

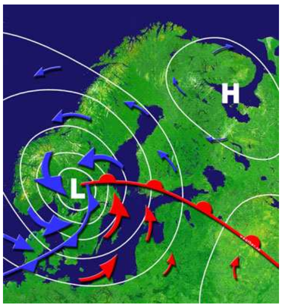


Figure 3.2: Schematic picture of the wind direction around a low pressure

In the north hemisphere the wind always blows anti clockwise around a low pressure. This means that north to the center the wind is blowing to the east, to west of the center the wind blows to the south and so fourth. See figure 3.2.

This is because of the earth rotation around its own axis and is a result of the coriolis force [4].
The interesting wind direction in our simulations is in fact not the actual direction but the angel the wind makes to the power line. Let the power line be located between the points (x_1, y_1) and (x_2, y_2) in figure 3.3. The center of the wind area is located in (μ_x, μ_y). The angle α is between 0 and π. Introduce the vector $\bar{r} = (x_1, y_1), (\mu_x, \mu_y)$ and $\bar{u} = (x_1, y_1), (x_2, y_2)$. Then α is given from the law of cosine; $\cos\alpha = \frac{\bar{r}\bar{u}}{|\bar{r}||\bar{u}|}$ and $\beta = \frac{\pi}{2} - \alpha$ if $\alpha \leq \frac{\pi}{2}$ and $\beta = \alpha - \frac{\pi}{2}$ if $\alpha \geq \frac{\pi}{2}$. β is always between 0 and $\frac{\pi}{2}$. The perpendicular wind component is then achieved from the multiplication $v_p(t) = \sin\beta(t)\ v(t)$
Both the mean wind and the maximal gust wind is supposed to have the same direction.

3.2 Precipitation

The precipitation area is more difficult to model than the wind area. The reasons for it comes from the fact that the area changes a lot as the cyclone matures. In figure 3.4 four schematic pictures of a typical cyclone is shown. It is approximately 12 hours between the pictures. We have chosen to try to model it as it looks in figure 3.4(c). The reason for that choice is that the cyclone normally is in its most violent and most active phase at that time[4]. We are

not interested in modelling the whole process of a cyclone, only a cyclone that can destroy the transmission network.
The precipitation area is modelled in two different parts. One part is the almost circular area close to the low pressure center. This is modelled with one function that gives the largest values in the center and decreasing values further out.

$$\begin{aligned} g(x,y,t) &= Ae^{(-\frac{1}{B}*(x-x_c(t))^2+(y-y_c(t))^2)} \\ \text{if } (x-x_c)^2 &+ (y-y_c)^2 < R^2 \\ &\text{else } g(x,y,t) = 0 \end{aligned} \tag{3.4}$$

$x_c(t)$ and $y_c(t)$ are the x and y coordinates for the low pressures center at time t. The constants A, B and R are chosen so the appropriate properties of the precipitation area are achieved. The constant A is giving the maximum precipitation rate in the center of the circle. For example $A = 10\ mm/h$. To model the decreasing intensity as we get further out from the center the constant B is important. $B = 3000$ gives a realistic distribution of the precipitation [7]. R is the radius of the circle and varies a lot between different storms. In the 1969 storm over the southern parts of Sweden the radius was about 300 km [12].
The frontzone is modelled with another function.

$$h(x,y,t) = Ke^{-\frac{1}{P}(y-y_c(t))^2} \tag{3.5}$$

In order to get the front zone in the right position i relation to the circular area described in (3.4) we have these restrictions.

$$\sqrt{\frac{(x-x_{fc}(t))^2}{0.8} + (y-y_{fc}(t))^2} > 1.1R \tag{3.6}$$

$$\sqrt{\frac{(x-x_{fc}(t))^2}{0.8} + (y-y_{fc}(t)^2} < 2.6R \tag{3.7}$$

$$x > x_{fc}(t) + 20$$

$$g(x,y,t) = 0$$

elsewhere

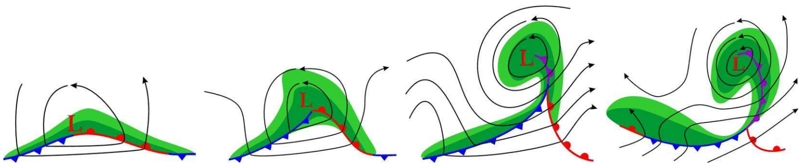
$$h(x,y,t) = 0. \tag{3.8}$$

Where:

$$x_{fc}(t) = x_c(t) - \frac{R}{2} \tag{3.9}$$

and

$$y_{fc}(t) = y_c(t) - 1.45R \tag{3.10}$$



(a) First (b) Second (c) Third (d) Fourth

Figure 3.4: The Norwegian cyclone model. [13]

are the center for the front zone at time t. The whole precipitation area is obtained by

$$f(x, y, t) = g(x, y, t) + h(x, y, t). \tag{3.11}$$

The front zone precipitation is modelled with the greatest intensity close to the low pressure center and then decreasing further out. The width of the front is dependent on the radius of the circle around the low pressure center. This is only to get the situation that a large precipitation area around the center is often (but not necessarily) followed by a large front zone. All these parameters are chosen with the knowledge of how difficult it is to model these kind of weather situations. The parameters are chosen so it is possible for the simulated weather to actually happen.

3.3 Movement

It is a very difficult matter to model how fast and in which direction a cyclone moves. Some cyclones move very fast and others move very slowly and might even become stationary. There is no obvious correlation between how fast a cyclone moves and how severe it is. There are other meteorologic conditions controlling the movement, such as jetstreams and pressure distribution high up in the atmosphere [4].
In Sweden most cyclones move from the Atlantic towards the east or north-east. This is the direction used in our simulations. The speed v has been approximated to 100 km/h. This value has been chosen since the very bad storm in 1969 moved approximately with that velocity [12]. The center of the cyclone moves according to the following equations.

$$x_c(t) = 0 + vtcos(\frac{\pi}{4}) \tag{3.12}$$

$$y_c(t) = 0 + vtsin(\frac{\pi}{4}) \tag{3.13}$$

The constant v is the speed of the cyclone. In our simulations, $v = 100$ km/h.

Chapter 4

Ice and snow accretion on power lines

There are many models available for how freezing rain and wet snow is deposited on different objects. It is for example of interest to study how high masts are effected by ice accretion in clouds in the northern part of Sweden. For transmission networks this problem seldom occurs since the poles are not high enough to reach the clouds and as a result ice accretion due to incloud icing is negligible [8].

The special property of freezing rain is that it falls as rain but as soon as it touches an object it freezes to ice. This is not a very rare weather phenomenon and in the normal case it has no great impact on power lines. Under very special circumstances heavier freezing rain falls and can be a great problem for power transmissions. Over the years a lot of research has been done about ice accretion on wires due to freezing rain. There are two different sorts of models, one uses physical parameters and determines the heat balance of the conductor. These models requires parameters that are difficult to model and therefore this approach is not used. The second kind of model uses meteorological data to compute the accreted ice.

The two models used here are the Goodwin et al.model from 1983 [17] and the "Simple model" by Kathleen F Jones [16]. We have chosen these models since they only need a few parameters, which are rather easy to estimate in a simulation of a storm.

4.1 The Goodwin and the Simple Model

In both the Goodwin model and the Simple model it is assumed that all the droplets that hits the surface of the wire freezes. That means no icicles are developed and the growth mode is said to be dry. This is one of the weaknesses with these models and one might think the model therefore overestimates the amount of ice accreted on the wire. However; that is not necessarily the case because the icicles which can be developed, but is ignored in the models, makes the area collecting new droplets larger. This in turn can make the model under estimate the ice load [14]. There are also numerical models available for ice accretion. These models take the wet growth into account and in [14] these things

are discussed. In the latest research the numerical calculations are regarded to be the most accurate. These things are further discussed in chapter 9.
Both the Goodwin model and the Simple model by Jones calculate the amount of rain that hits the wire from a horizontal and a vertical direction.
The massflux is the mass of rain that hits an area per time unit.
The vertical massflux can be calculated in two ways.

$$m_v = H_g \delta \tag{4.1}$$

where H_g is the precipitation rate and δ the water density, but the vertical massflux can also be calculated from the amount of water falling, $w(g/cm^3)$, in the air at terminal velocity, $V_t(m/s)$

$$m_v = 3.6 V_t w. \tag{4.2}$$

Let the horizontal wind speed be V_w then the horizontal massflux is given by:

$$m_h = 3.6 V_w w. \tag{4.3}$$

Assuming (4.1) and (4.2) are equal gives

$$w = \frac{H_g \delta}{3.6 V_t} \tag{4.4}$$

putting (4.4) into (4.3) gives

$$m_h = H_g \delta \frac{V_w}{V_t} \tag{4.5}$$

The total massflux hitting the line is

$$m_0 = \sqrt{m_h^2 + m_v^2}. \tag{4.6}$$

In the Simple model we get:

$$m_0 = \sqrt{H_g^2 \delta_w^2 + 3.6^2 V_w^2 w^2} \tag{4.7}$$

and in the Goodwin model we get:

$$m_0 = \sqrt{H_g^2 \delta_w^2 + H_g^2 \delta_w^2 \frac{V_w^2}{V_t^2}} = H_g \delta_w \sqrt{1 + \frac{V_w^2}{V_t^2}} \tag{4.8}$$

Different models assumes different shapes of the ice accretion around the power line. For example Chaine and Castongay assumes an elliptic accretion shape. However both the Goodwin and Simple model assumes a perfect circular shape. This is possible because of the power lines ability to rotate. When one side of the line has been covered with snow and ice it gets heavier and is rotated towards the ground and a new part of the line is exposed to the precipitation [5].
The ice thickness, R (mm), around the line when a circular shape is assumed, is given by:

$$R = \frac{m_0}{\pi \delta_i} \tag{4.9}$$

where δ_i is in g/cm^3. This leads to the increase of the radius of the accreted ice according to Goodwin:

$$\Delta R = \frac{H_g \delta_w}{\delta_i \pi} \sqrt{1 + \frac{V_w^2}{V_t^2}} \tag{4.10}$$

and according to the Simple model:

$$\Delta R = \frac{1}{\delta_i \pi} \sqrt{(H_g \delta_w)^2 + (3.6 V_w w)^2} \tag{4.11}$$

When freezing rain falls the droplets are often rather small. A diameter of 0.5 mm to 2 mm is therefore a good approximation. The fall speed of such droplets is between 2 m/s and 6 m/s. To use the Goodwin model a better knowledge of the speed of the falling drops is needed. The idea is to approximate the drop size and thereafter approximate the fall speed which is given as a function of the drop size.

In The Best article on the drop size distribution [15] the median drop diameter $d_m(mm)$ is estimated according to:

$$d_m = a 0.681^{\frac{1}{n}}. \tag{4.12}$$

Where a is found from the precipitation rate H_g.

$$a = A H_g^p \tag{4.13}$$

The constants A and p has been calculated experimentally by a number of scientists and the numbers accepted for freezing precipitation are the values given by Marshall and Palmer(1948). $A = 1, p = 0.240, n = 1.85$.

According to The Best paper [15] the drop velocity can be given by

$$V_t = 10.3 - 9.65 e^{-0.6 d_m}. \tag{4.14}$$

This approximation of the drop fall speed is used in the Goodwin model. It gives a good fit for diameters larger than 0.4 mm. For very small drop diameters the Best model predicts negative fall speeds. This is not a problem in our simulations since we only have fairly large precipitation levels and therefore also fairly large drop diameters.

In the Simple model the liquid water content must be calculated. According to The Best paper [15] the liquid water content is given by

$$w = 0.072 H_g^{0.88}. \tag{4.15}$$

The constants are given from Marshall and Palmer(1948)

By looking at the formula (4.10) a smaller value on the fall speed will increase the ice accretion rate. In neither of these two models the radius of the line is part of the formula. Therefore the accreted ice thickness does not depend on the initial radius of the line. However; the weight of the accreted ice is greater if the line is thicker. In these models the wind perpendicular to the line is of interest.

The density of the accreted ice is a question that offers some difficulties. In the literature the heaviest ice that can be developed has a weight of approximately 0.9 kg/dm^3 [5]. It is though unlikely that such heavy ice is created because the situation must be absolutely perfect. In the severe ice storm in 1921 in southern parts of Sweden ice with the density of 0.6-0.7 kg/dm^3 was found [11].

4.2 Differences between Goodwin and the Simple model

The two models differ in their calculation of the horizontal contribution to the massflux. The Simple model uses the liquid water content-approach, equation (4.3), and the Goodwin model uses the precipitation rate-approach in combination with the droplets fall speed, equation (4.5). In a situation with no wind at all the two models are equal since $V_w = 0$ in (4.11) and in (4.10). When the wind $V_w \neq 0$ the second term in (4.11) and in (4.10) makes the two models different from each other. Parameters like the drop fall speed and the liquid water content are important for the results. When these models were developed, no specification was made about how the drop fall speed and liquid water content should be calculated so the choice of method for these calculations has an influence on the result.
To see how the two ice accretion models used in this report differs, four simulations have been done. The cyclone model developed in chapter 3 has been used to create different weather situations. The two models have been tested, to see whether they respond differently to changes in wind and precipitation levels. We have already noticed that in the no-wind-situation they yield the same result. In all four simulations below the wind speed presented is the maximum gust wind and a line with a diameter of 30 mm has been used.
In table 4.1 the four simulations are showed.

Sim nr	Description	Result
1	Light winds	Equal
2	Strong winds	Simple>Goodwin
3	Heavy precipitation	Simple>Goodwin
4	Light precipitation	Simple>Goodwin

Table 4.1: Simulations performed

4.2.1 Simulation 1

In the first simulation we used a maximum precipitation rate of ($7mm/h$) and light winds ($5m/s$) in our cyclone model.

From figure 4.1 it can be seen that there are fairly small differences between the two models.

4.2.2 Simulation 2

In the second simulation we used a maximum precipitation rate of ($7mm/h$) and strong winds ($35m/s$) in our cyclone model.

From figure 4.2 it can be seen that the differences are much larger than in simulation 1. The Simple model gives approximately 13% larger values for the ice accretion than in simulation 1.

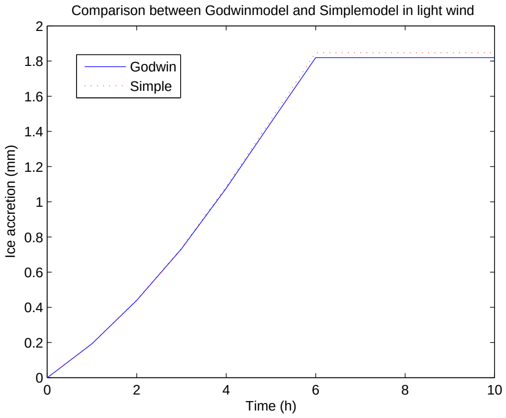


Figure 4.1: Comparison in light winds

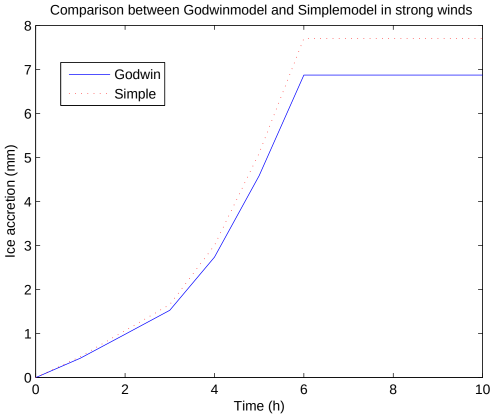


Figure 4.2: Comparison in strong winds

4.2.3 Simulation 3

In the third simulation we used a maximum precipitation rate of $(12mm/h)$ and medium winds $(20m/s)$ in our cyclone model.

From figure 4.3 it can be seen that in heavy precipitation the Simple model gives larger ice accretion than the Goodwin model. Approximately 10%.

4.2.4 Simulation 4

In the fourth simulation we used a maximum precipitation rate of $(2mm/h)$ and medium winds $(20m/s)$ in our cyclone model.

From figure 4.4 it can be seen that the differences are a fraction less than in simulation 2 and simulation 3.

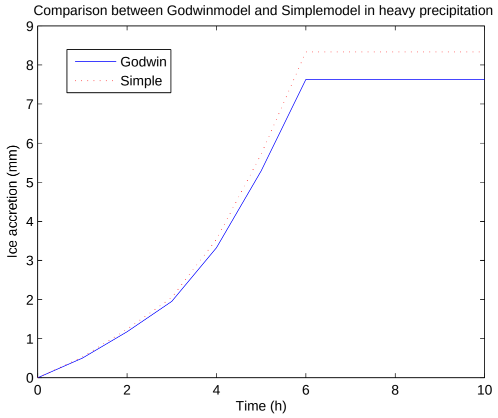


Figure 4.3: Comparison in heavy precipitation

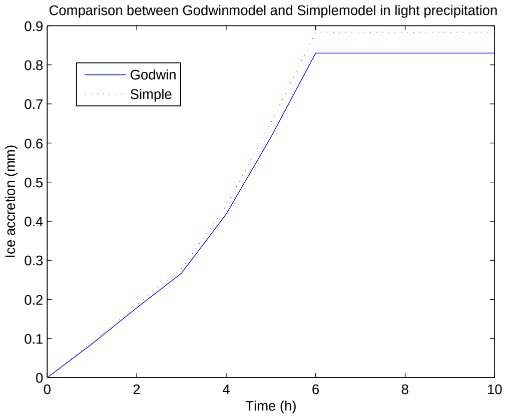


Figure 4.4: Comparison in light precipitation

4.3 Wet snow accretion

The Goodwin and Simple model described above has been developed to model the effects of freezing rain. However; to model wet snow accretion on power lines, which is a more common phenomenon, the Goodwin model can be used. Sakamoto and Ishihara developed a formula that is exactly the same as the Goodwin model to model snow accretion in Japan. The only things that differs from the freezing rain model is the density of the accretion and the fall speed of the precipitation. For wet snow a density of $0.3 - 0.6 kg/dm^3$ is an accepted choice [5]. The fall speed of the snowflakes is also a problem since it differs a lot because of the large variety of the snowflakes size.

Chapter 5

Power lines

In the numerical examples we have studied two existing power lines.

5.1 Hisingen-Kilanda

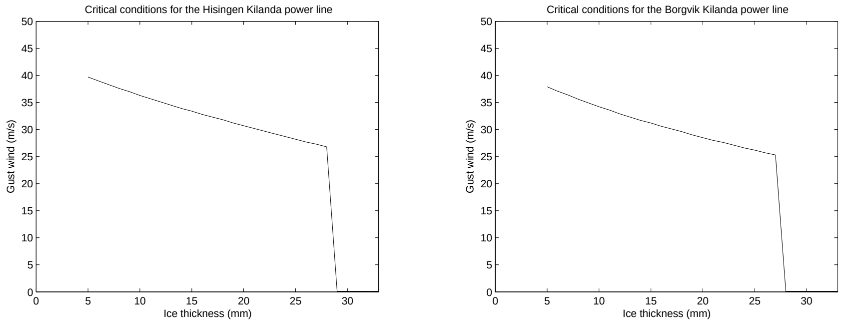
The 400 kV power line between Hisingen and Kilanda is studied. It consists of two lines, one phase line with a diameter of 36.2 mm and a top line with a diameter of 20.1 mm. The line is 29 km and consists of 91 poles, 61 of them are of a model called A2 or A2X. The calculations on the risk of breakdown is performed on these poles and the other 30 poles are supposed to breakdown at the same rate. The ice load and wind calculations are made at the midpoint of the line. The same weather situation is expected on the whole line. It is a reasonable estimation since the line is relatively short. The line goes in a northeast-southwest direction and is therefore most vulnerable to winds from the north-west and south-east.

5.2 Kilanda-Borgvik

The 400 kV power line between Kilanda and Borgvik is approximately 177 km and consists of 513 poles. Of those 361 are of a model called A1 or A1X. The phase line has a diameter of 31.7 mm and the there are two different top lines. In some places a line with a diameter of 20.1 mm is used and at other places the diameter is only 10.6 mm. The line goes in a north-south direction.

5.3 Critical loads for the power lines

The Hisingen Kilanda poles are designed to stand an ice load of 2.76 kg/m and a gust wind of 28 m/s at the same time [18]. In our simulations the ice and wind loads are varied, and some knowledge of how an increased ice load influence the critical gust wind is necessary. Vattenfall power consultants have performed a detailed calculation on when the first pole break down at different ice and wind loads. The result of this calculation can be seen in figure 5.1. The same calculations have been performed on the Borgvik Kilanda power line, also presented in figure 5.1.



(a) Critical loads for the Hisingen Kilanda power line

(b) Critical loads for the Borgvik Kilanda power line

Figure 5.1: Critical loads for the studied power lines

In these calculations the density of the ice is 900 kg/m^3.
When the ice thickness exeeds 28 mm at the Kilanda Hisingen power line and 27 mm at the Borgvik Kilanda power line, the weakest pole breaks because of the ice load alone. For all loads under and to the left of the plotted line in figure 5.1 the poles are supposed to hold.

5.4 Heating of power lines

As the current flows through the power line, it is heated up. In special situations the line can get up to twenty degrees warmer than the air temperature [18]. We have assumed, in all our simulations, that this heating effect do not prevent the ice from building up on the power line. When the ice has started to build, the heat gets isolated inside the ice, and does not influence the continuous ice accretion [18].

Figure 5.2: The studied power lines

Chapter 6

Weather observations

The Swedish Meteorological and Hydrological Institute (SMHI) has provided some simulated data from two storms in the southern parts of Sweden. The first occurred in November 1995 and the second in December 1999. The data contains information on precipitation, mean wind, max gust wind and wind direction every third hour for different coordinates.
The first storm was a storm with a lot of wet snow falling. The winds were strong with gust wind speeds reaching strong gale. The second was an even worse cyclone, gust wind speeds reaching 32 m/s. The temperatures were a little higher than in the 1995 storm and most of the precipitation fell as rain.
We have made an assumption that the temperatures would have been ideal for the precipitation to fall as freezing rain in both these storms. This is not unrealistic [7]. This assumption makes it possible to see how the ice loads are developed on the transmission lines and what happens when the ice load and the winds are taken from a semi-authentic situation.

Another possibility is to rescale the precipitation rates. In both storms it is not impossible to increase them with a factor up to 70 percent, and in some cases even 150%, given the relatively low precipitation rates [7]. This will give us the possibility to simulate a storm that only will occur in Sweden about once in 200 years.

In both severe ice storms in the 20:th century that has taken place in the southern parts of Sweden the winds have blown from the north-east [10] [19]. Both these storms used in the above described simulations have winds blowing from the west. Most storms in Sweden have the strongest winds from that direction but it is a possibility that ice storms easier develops with winds from north-east.

Chapter 7

Simulations

In all simulations the accreted ice on the power lines is supposed to have the density, $\delta = 900\ kg/m^3$.

7.1 The 1995-storm

Two simulations based on the 1995 storm is presented here. In both these simulations the precipitation is supposed to fall as freezing rain.

7.1.1 Hisingen-Kilanda Simulation 1

In the first simulation the storm is used without any manipulation except that the precipitation is supposed to fall as freezing rain. In the real case wet snow was falling. The precipitation at the location of the power line is shown in figure 7.1.

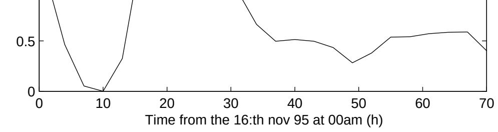
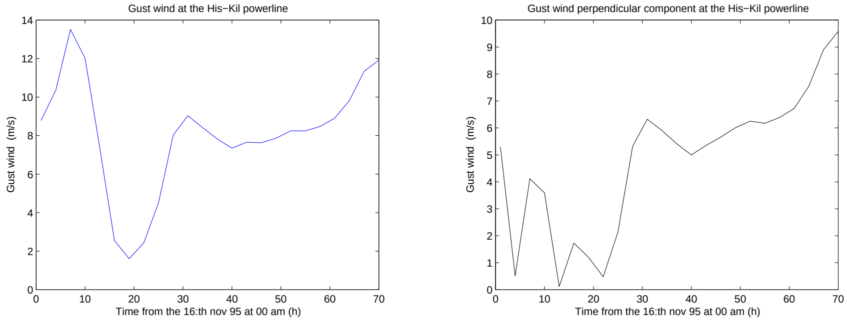


Figure 7.1: The precipitation at the Hisingen-Kilanda power line in November 95

The totally accumulated precipitation is 21 mm. The gust wind and the gust wind´s perpendicular component to the power line is showed in figure 7.2.

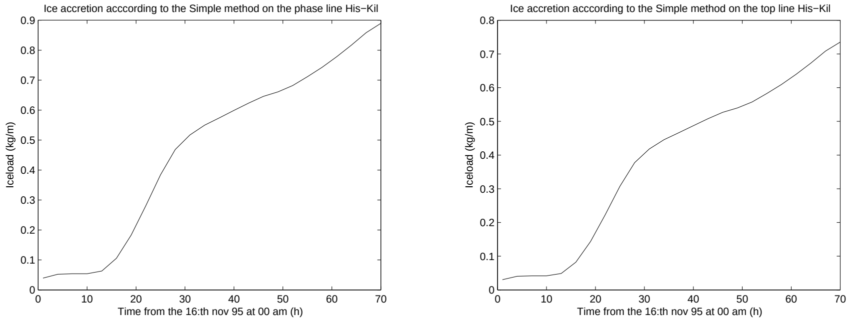


(a) Gust wind

(b) Gust wind perpendicular to the line

Figure 7.2: Gust winds during the 95-storm at Hisingen-Kilanda power line

Notice how the wind turns by comparing the two graphs in figure 7.2. In the first 10 hours the wind blows much more parallel to the line than in the later stages of the storm.



(a) Ice accretion on the phase line

(b) Ice accretion on the top line

Figure 7.3: Ice accretion in kg/m

The ice accretion on the phase line according to the Simple model is showed in figure 7.3(a), and the ice accretion on the top line is showed in figure 7.3(b). In figure 7.4 the loads from the "Hisingen Kilanda Simulation 1" is compared to the critical loads. In this simulation the loads are never close to damaging the line.

7.1.2 Hisingen-Kilanda Simulation 2

In the second simulation the precipitation is increased by 150% and the winds by 50% compared to the original storm data from 1995. The new precipitation is showed as a function of time in figure 7.5.

The new wind speeds are shown i figure 7.6.

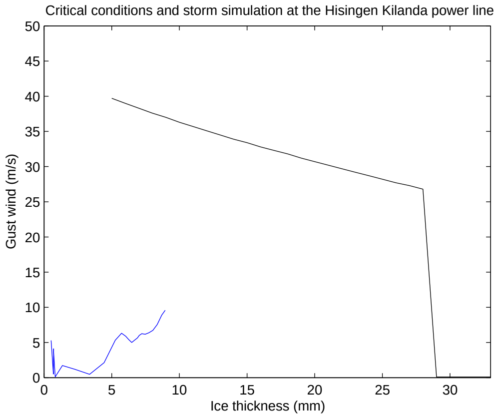


Figure 7.4: Loads of "Hisingen Kilanda Simulation 1" compared to the critical loads

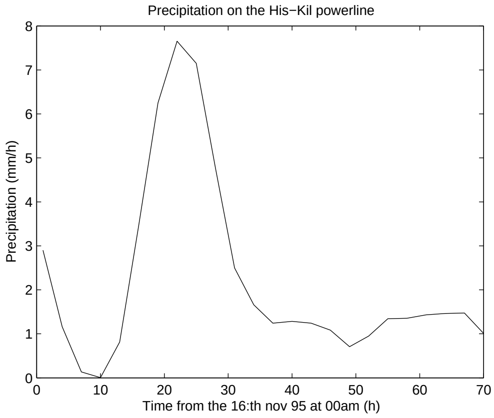
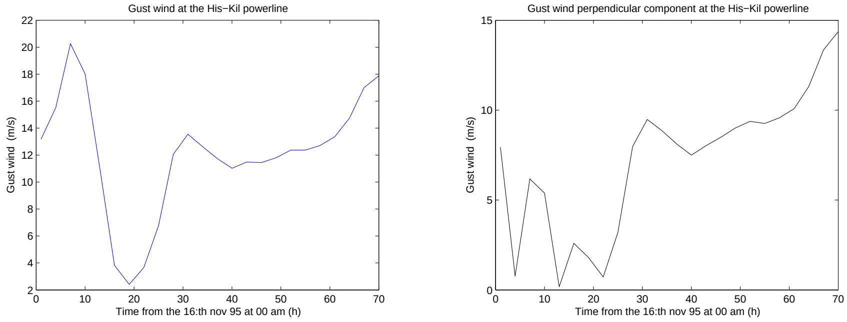


Figure 7.5: The precipitation when increased by 150%

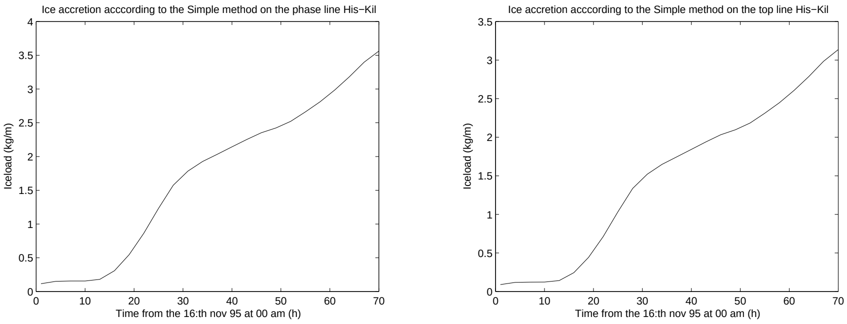
The wind direction is not changed compared to Simulation 1. Still the winds turn more and more perpendicular to the line as time move on.
The ice accretion according to the Simple model is shown in figure 7.7. The left graph shows the ice accretion on the phase line and the right graph shows the ice accretion on the top line. It is interesting to notice, how important the wind direction is in creating an ice layer. The ice layer builds almost as fast the latest 20 hours when the precipitation intensity is just 25% of the intensity earlier in the studied time interval. During these last 20 hours the wind has turned around, and is almost perpendicular to the line which results in a faster ice accretion. In figure 7.8 the loads from the "Hisingen Kilanda Simulation 2" is compared to the critical loads. The increased wind and precipitation have narrowed the margin between the loads in the simulation and the critical loads, but still there are no poles in danger of breaking down.



(a) Gust wind when increased by 50%

(b) Gust wind perpendicular to the line when increased by 50%

Figure 7.6: Gust winds during the 95-storm at Hisingen-Kilanda power line when increased by 50%



(a) Ice accretion on the phase line

(b) Ice accretion on the top line

Figure 7.7: Ice accretion in kg/m

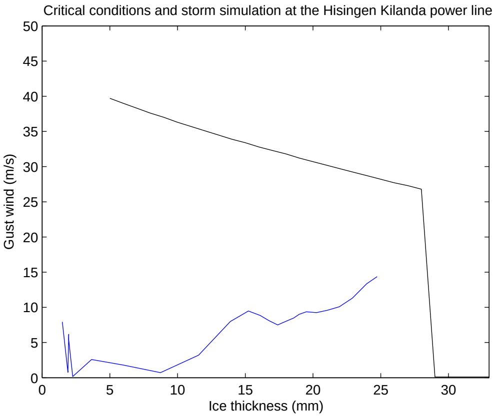


Figure 7.8: Loads of "Hisingen Kilanda Simulation 2" compared to the critical loads

7.2 The 1999-storm

A number of simulations have been made with the data from the storm in December 1999. Three of them are described in details here.
The temperatures were a few degrees over 0°C and most of the precipitation fell as rain. It would have been possible to have the same situation with just a few degrees lower temperature and the rain could then be falling as freezing rain instead [7]. This is assumed in the following simulations.
To simulate an even worse weather the precipitation and wind speeds are increased in some simulations. The reason for these changes is to get the possibility to model a weather situation that only might occur once in a one or twohundred year period.

7.2.1 Hisingen-Kilanda Simulation 3

In the ´Hisingen Kilanda simulation 3´ the storm was used without any manipulation except that the precipitation is supposed to fall as freezing rain. In the real case wet snow and rain fell. The precipitation at the location of the power line is shown in figure 7.9.

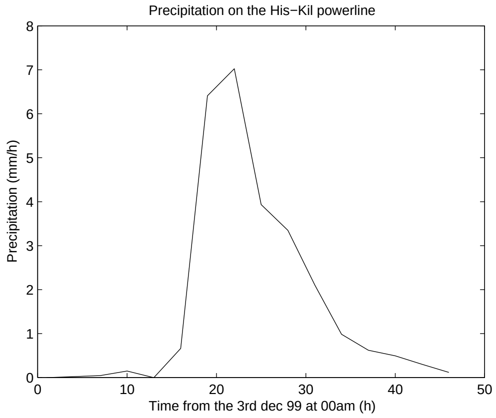
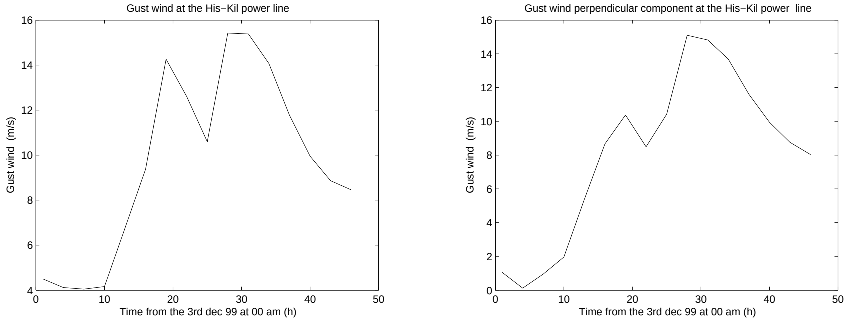


Figure 7.9: The precipitation at the Hisingen-Kilanda power line

The totally accumulated precipitation is 26 *mm*. The gust wind and the gust wind´s perpendicular component to the power line is showed in figure 7.10.

It is interesting to see that the first peak in the gust wind graph is not at all seen in the perpendicular gust wind speed graph. The direction of the wind at that time was almost parallell to the line. A few hours later the wind had turned around so the wind affects the line a lot more.

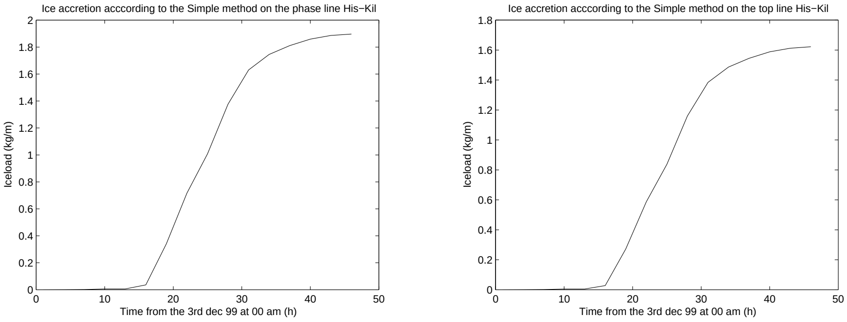
The ice accretion on the phase line according to the Simple model is showed in figure 7.11(a), and the ice accretion on the top line is showed in figure 7.11(b)
In figure 7.12 the loads from the "Hisingen Kilanda Simulation 3" is compared



(a) Gust wind

(b) Gust wind perpendicular to the line

Figure 7.10: Gust winds during the 99-storm at Hisingen-Kilanda power line



(a) Ice accretion on the phase line

(b) Ice accretion on the top line

Figure 7.11: Ice accretion in kg/m

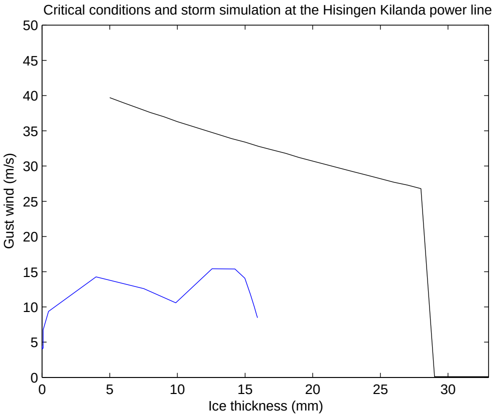


Figure 7.12: Loads of "Hisingen Kilanda Simulation 3" compared to the critical loads

to the critical loads. Notice that during the storm the loads are never close to damaging the line.

7.2.2 Hisingen-Kilanda Simulation 4

In the fourth simulation the precipitation is increased by 70%. The precipitation is showed as a function of time in figure 7.13.

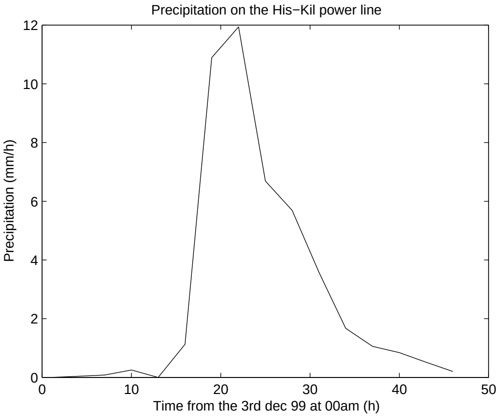
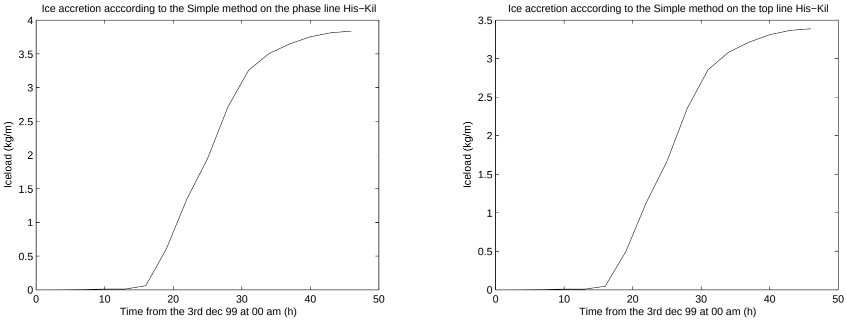


Figure 7.13: The precipitation when increased with 70%

The wind is the same as in 7.2.1. The ice accretion according to the Simple model is shown in figure 7.14. The left graph shows the ice accretion on the phase line and the right graph shows the ice accretion on the top line.



(a) Ice accretion on the phase line

(b) Ice accretion on the top line

Figure 7.14: Ice accretion in kg/m

In figure 7.15 the loads from the "Hisingen Kilanda Simulation 2" is compared to the loads that are supposed to cause damage to the poles of the line. Notice that during the storm the loads are never close to damaging the line until the end, when the ice load is rather close to breaking at least a few poles.

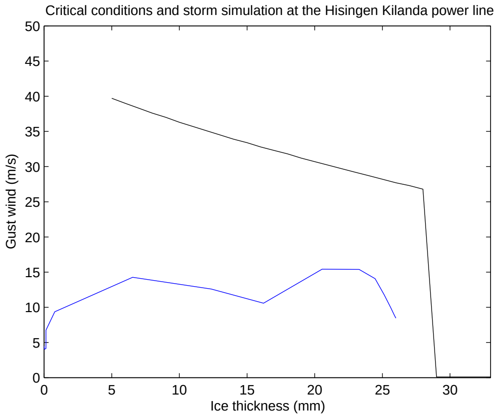


Figure 7.15: Loads in "Hisingen Kilanda Simulation 4" compared to the critical loads

7.2.3 Hisingen-Kilanda Simulation 5

In the fifth simulation the precipitation is not changed compared to original data from 1999. This means that the precipitation is the same as in section 7.2.1.

The wind is increased by 100% compared to original data. The new winds are shown in figure 7.16.

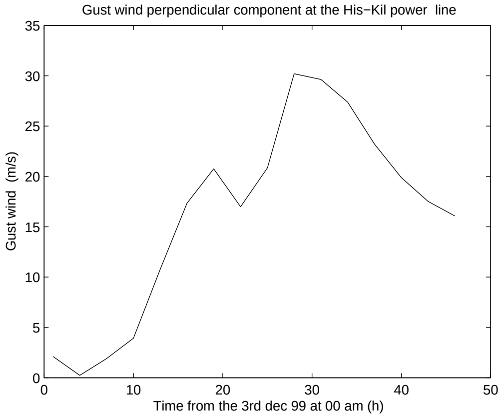
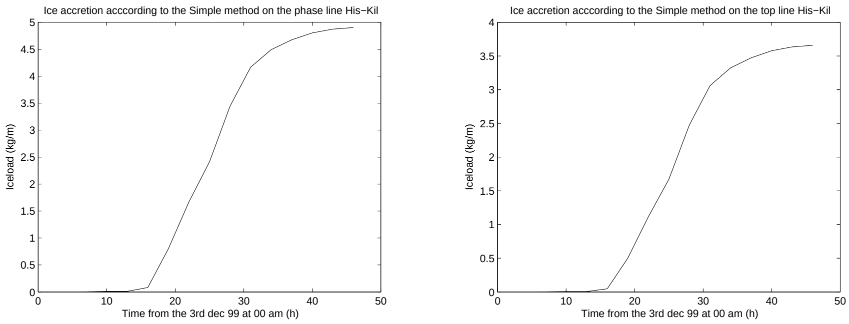


Figure 7.16: The gust wind perpendicular component when increased by 100%

This is not a completely unlikely scenario since Sweden has been hit by storms with winds as strong as in this simulation before [20]. The ice accretion according to the Simple model is shown in figure 7.17. The left graph shows the ice accretion on the phase line and the right graph shows the ice accretion on the top line.

In figure 7.18 the loads from the "Hisingen Kilanda Simulation 5" is compared to the loads that are supposed to cause damage to the poles of the line.



(a) Ice accretion on the phase line

(b) Ice accretion on the top line

Figure 7.17: Ice accretion in kg/m

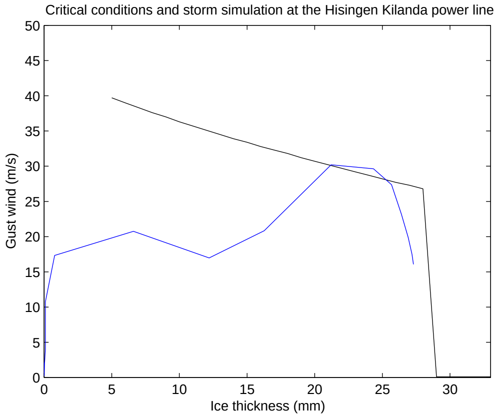


Figure 7.18: Loads in "Hisingen Kilanda Simulation 5" compared to the critical loads

7.3 Using the cyclone model

A few special cases have been studied by using our own cyclone model.

7.3.1 Storm moving parallel to the Borgvik Kilanda power line

An interesting phenomenon occurs if the cyclone moves parallel to the power line and the center moves very close to the line. See figure 7.19.

The result is that the wind is almost all the time perpendicular to the power line. As a result the power line is exposed to much more precipitation and the wind force on the lines will be much larger.
In the simulation we have used a maximum precipitation rate of 7 mm/h and a maximum gust wind of 25 m/s. The precipitation as a function of time is seen in figure 7.20.

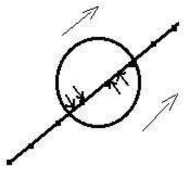


Figure 7.19: Storm moving parallel to the power line

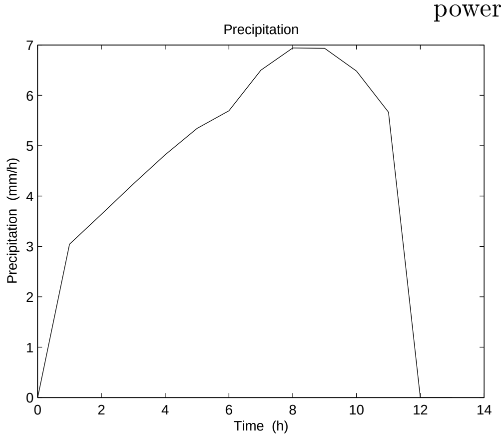
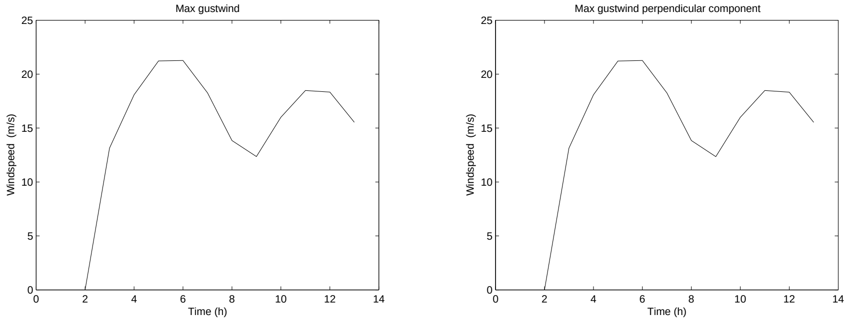


Figure 7.20: The precipitation

In figure 7.21 the gust winds are shown. In the left, the gust wind, and in the right, the gust wind´s perpendicular component to the power line.



(a) Gust wind

(b) Gust wind perpendicular to the line

Figure 7.21: Gust winds

Notice that in figure 7.21 the perpendicular component is as large as the gust wind itself. The conclusion is that the wind is perpendicular to the line at all times.
The ice accretion as a function of time according to the Simple model is given

in figure 7.22.

In figure 7.23 the loads simulated are compared to the critical loads.

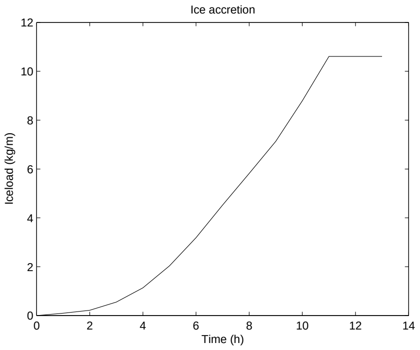


Figure 7.22: The ice load in kg/m

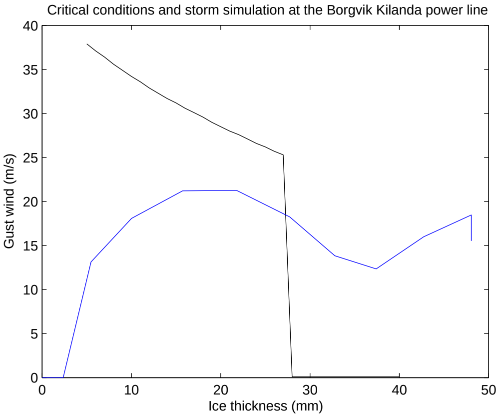


Figure 7.23: Simulated loads compared to the critical loads for the Borgvik Kilanda line

7.3.2 Storm moving perpendicular to the Borgvik Kilanda power line

To compare the result of the simulation in section 7.3.1, a simulation with the storm moving perpendicular to the power line is performed. This simulation shows that the wind is almost all the time parallel to the power line. As a result the power line is exposed to a minimum of precipitation and wind force.

In the simulation we have used a maximum precipitation rate of 7 mm/h and a maximum gust wind of 25 m/s. This is exactly the same as in the simulation described in section 7.3.1. At the point of measurements on the line, exactly the same weather conditions are chosen. The only thing that differs are the movement of the storm, and the wind direction.

The precipitation as a function of time is seen in figure 7.24

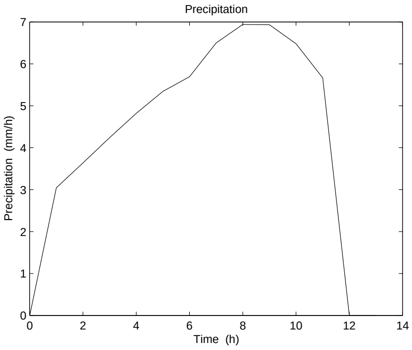
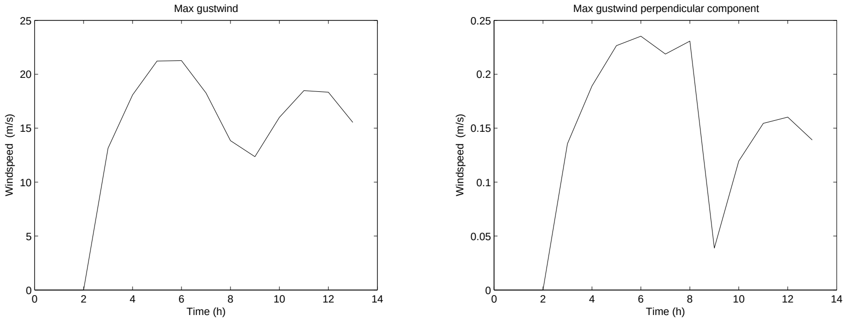


Figure 7.24: The precipitation

In figure 7.25 the gust winds are shown. In the left figure the gust wind is shown and in the right figure the gust wind´s perpendicular component to the power line is shown.



(a) Gust wind

(b) Gust wind perpendicular to the line

Figure 7.25: Gust winds

The most interesting thing in the comparison between the two figures in figure 7.25 is that the perpendicular component is almost 0. The conclusion is that the wind is parallel to the line at all times.
The ice accretion as a function of time according to the Simple model is given in figure 7.26

The ice load is approximately 3 kg/m on the wires which is only 25% of the load in the simulation in section 7.3.1.
In figure 7.27 the loads are compared to the crititcal loads on the Borgvik Kilanda power line.

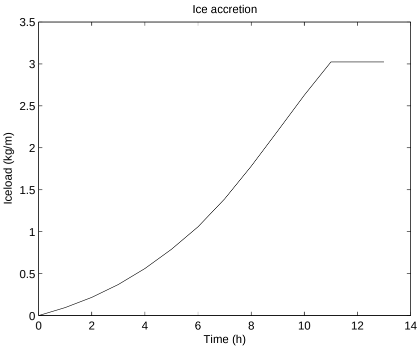


Figure 7.26: The ice load in kg/m

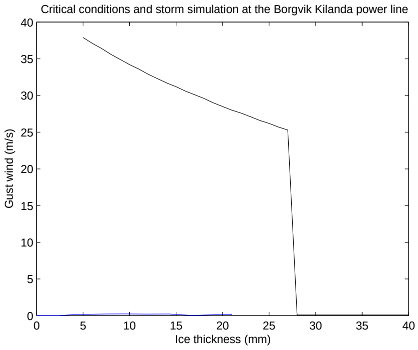


Figure 7.27: Simulated loads compared to the critical loads for the Borgvik Kilanda line

Chapter 8

Results

8.1 Differences between Goodwin and the Simple model

When there is no wind, or very light wind, the differences between the two models are negligible. In the simulations described in section 4.2 it was shown that with increasing wind the differences increased, but the sensitivity to the precipitation rate was very weak. The Goodwin model is very sensitive to the choice of droplet fall speed and how that is calculated. With a fall speed less than 3 m/s the Goodwin model often gives larger values for the ice accretion than the Simple model. With our choice of calculation of drop fall speed (The Best approach) the drop fall speed is seldom less than 4 m/s. For the sensitivity of drop fall speed and the problems to model that, the Simple method is maybe to prefer in our simulations.

8.2 The 1995 storm

The storm in November 1995 simulated in section 7.1.1 does not lead to any kind of damage to the poles. The poles are designed for much worse storms, both in respect of ice loads and wind force.
In simulation 7.1.2 the wind and precipitation are increased but still the poles hold. This is seen in figure 7.8 when the critical loads are compared to the simulated loads. If the storm would have continued for another 5 hours the ice load might have caused some poles to break.

8.3 The 1999 storm

In the simulation described in section 7.2.1 the loads are to small for any poles to break, especially the gust wind is too weak.
It is not likely that the weather simulated in section 7.2.2 will cause any damage either. Towards the end of the simulated storm the ice loads are close to what is critical for the poles, but still the poles are supposed to hold.
In the fifth simulation, described in section 7.2.3, the ice and wind loads are larger than in the other simulations. In figure 7.18 it is seen that the wind and

ice loads exceed what is calculated to be the critical loads for the line. The conclusion is that some poles will be broken by the loads.

8.4 Using the cyclone model

The two simulations on the Borgvik Kilanda power line, using our own cyclone model described in sections 7.3.1 and 7.3.2, show the importance of the wind direction. Exactly the same weather conditions are used in the two simulations with the exception of the movement of the cyclone. In the first simulation the cyclone moves parallel to the power line which leads to a situation where the wind is perpendicular to the line at all times. This wind direction makes a much faster ice accretion possible. The loads are so large that a number of poles will break for the ice load. This is seen in figure 7.23.

In the second simulation the wind is blowing parallel to the line and the ice accretion is therefore a much slower process. The loads are not close to causing any damage to the power line as can be seen in figure 7.27.

Chapter 9

Discussion

9.1 Improving the study

The methods for calculating the ice loads used in this report are maybe not the most accurate methods available. The latest research is focusing on numerical methods that takes for example icicles into account. Using these newer methods instead, might improve the result of the study. To do this, even more meteorological data must be available, for example the humidity.

Another problem that has not been studied in detail is the heating of the power lines. We have expected the precipitation to be strong enough for a layer of ice to develop on the lines although the lines are warmer than the surrounding. At what temperatures are that a reasonable estimation? In reality some freezing rain will not be freezing because of the heat the power line produces. This problem has not been considered in this report and might very well have an influence on the results.

In all the simulations in this report the ice density of 900 kg/m^3 has been used. This is the heaviest form of ice that possibly can be accreted on power lines by freezing rain [5]. However; a lower ice density would increase the wind force on the poles since the ice layer would be thicker given the same precipitation rate. The thicker ice layer would make the exposed area to wind larger which leads to the increased wind force. How these things effects the results have not been fully investigated.

In chapter 6 it was discussed what was the most likely wind direction in Sweden during an ice storm. During the two most severe ice storms in southern Sweden the last hundred years the wind has blown from the north-east. Both storms used in the simulations in this report had winds mainly from the west and south-west. It would be very interesting to run a simulation with a storm with the winds from the north-east, but the lack of resources for this, has forced us to give up that ambition.

9.2 Critical weather situations

The calculations on the risk of breakdown of poles, has shown that a gust wind perpendicular to the power line of 30 m/s and an ice load of approximately 4.0 kg/m is maybe a critical load to the poles. What kind of weather situation will

put this load on the power lines?
Here are a few examples:

- Gust winds of 25 m/s with the wind direction turning around so the wind at some times blows almost parallel to the line and at other times almost perpendicular to the line. 8 mm/h of freezing rain falls for 10 hours.
- Gust winds blowing almost parallel to the line during the precipitation for 20 hours. The precipitation rate in average 5 mm/h. Towards the end of the storm the wind turns and gust winds of 30 m/s blows perpendicular to the line.
- Three days of fairly light freezing precipitation of approximately 1.5 mm/h and moderate winds most of the time perpendicular or close to perpendicular to the power line. Towards the end of the period the gust winds reach 35 m/s in a direction that is close to perpendicular to the power line.

It is not unusual for the wind direction to change during a storm [4]. Therefore it is a very complex situation to describe a storm in a few words, and the examples above, are just an idea of what might be a reasonable scenario.
These weather conditions that might cause poles to break are very rare in Sweden, and therefore power outages because of broken poles are not very likely. We should, however, remember that the calculations only show that the risk for broken poles are small, but power outages of other reasons due to the storm, has not been considered at all.

Chapter 10

Conclusions

This master thesis has described the development of a weather model for severe storms and ice storms. Mathematical functions have described the patterns of precipitation and wind. Also the geographical movement of the storm has been modelled.
The ice accretion on power lines have been modelled by two different models, The Goodwin Model and The Simple model. Differences between these two models have been simulated and discussed. Estimations of the effects of our simulated ice storms have been presented based on some detailed calculations on two specific power lines in southern Sweden. In addition, data from two authentic storms have been analysed, and used in simulations. The effects of these storms have been presented in detail.

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