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Structural reliability analysis of transmission line towers by use of advanced weather modelling

Andreas I. LEM*	**Øystein LANDE**	**Sigbjørn GRINI**	**Jon. P. NORHEIM**
Statnett SF	**DNV**	**Kjeller Vindteknikk**	**Statnett SF**
Norway	**Norway**	**Norway**	**Norway**
Andreasistadlem@ gmail.com	**Oystein.lande@ Dnv.com**	**sigbjorn.grini@ norconsult.com**	**Jon.norheim@ Statnett.no**

SUMMARY

Statnett has developed a probabilistic approach to transmission line dimensioning, as described in paper B2-102 for the CIGRE 2020 session [1]. Based on findings in the 2020 work, several improvements have been made. This paper details the theory behind the latest methodology improvements. In addition, real-life calculation examples are emphasized. One analysis example describes reasonably benign loading, at low altitudes in a fjord in Norway with heavy winds and low icing loads. Another example describes a high-altitude area with extreme ice loading, probably one of the worst areas in the world, combined with high wind loads. Common for both transmission lines is a complex geographic topology, which is not easily represented by statistical environmental distributions.

The main aim is to extend the life of assets, which will have a big impact for Statnett, with potential savings of several tens of M€. And for assets where reinforcements are needed, the current methodology will much more accurately pinpoint the towers and tower-members that require special attention. Instead of reinforcing a whole section, Statnett can more reliably choose individual members, thanks to the new methodology.

Trust in the new tool is a potential hurdle for further use. However, with the greatly improved weather modelling presented in this paper, a much more reliable weather modelling is possible compared with the current practice, where load cases are defined a-priori. This removes a lot of uncertainty with a new modelling tool. Going forward focus will be to gain experience, and with that a better interpretation of results from the new methodology.

* andreasistadlem@gmail.com

KEYWORDS

Transmission tower, Reliability, Life extension, Weather modelling, Monte-Carlo, Failure probability

Background

Statnett is Norway's central grid operator, and currently owns roughly 11 000 km of high voltage transmission lines, whereof a substantial part nears the end of their design lives. To quantify the state of the assets and the failure probability related to a possible lifetime extension, Statnett has developed a probabilistic methodology together with DNV and KVT. The first edition of this approach is described in detail in CIGRE paper B2-102 [1]. Three main improvements have been made since, such that all major failure modes are now accounted for:

i) The weather modelling is greatly improved to model the environmental loads more accurately.
ii) Stochastic tower, foundation and conductor / earth wire capacities are used.
iii) Conductor / earth wire breakage (rupture) is implemented so that realistic loading conditions can be combined with sudden un-balanced loading due to line breakage.

The methodology is written in the Python programming language. This new tool is called ProTECT (Probabilistic Tool for Evaluating Components of Transmission lines).

Methodology – in brief

Weather time series are generated in several steps. First, hindcast weather data is modelled using the Weather Research and Forecasting (WRF) numerical weather prediction model. In turn a multivariate statistical model is fitted to the hind-cast data. By use of advanced copulae a superior correlation can be obtained, both between spatial points and between different parameters, i.e. temperature, wind speed and wind direction. The fitted statistical distributions enable the generation of synthetic weather time series for long-term analysis by Monte-Carlo simulation. These time series, of wind speed, wind direction, temperature and ice loads, provide realistic weather conditions for each transmission tower and line segment. This greatly improves the accuracy compared to the pre-defined (a-priori) load cases presently used with the deterministic approach.

Stochastic capacities are generated by defining statistical distributions for all relevant design parameters, and thereafter evaluating the governing design codes with input parameters drawn from the defined distributions. The governing codes for steel, concrete and geotechnical capacities are EN1993, EN1992 and EN 50341-2-16, respectively. All relevant checks / formulae in these standards are evaluated when calculating tower and foundation capacities.

The structural reliability analysis evaluates loading from the synthetic time series against stochastic capacities for all tower and foundation members. A member capacity does not vary from one load cycle to the next. Instead, the capacity is defined as unchanged in its design life, typically 50 years. For the next 50 years a new capacity is calculated. This continues for the chosen number of design life cycles; 100, 1000 or more. Based on these analyses the failure probability is obtained, for all towers, one tower, one foundation or one member.

Stochastic capacity modelling

General

Member capacities for steel beams, concrete, wires and conductors rely on both material properties and member geometry. This is reflected in the parameters governing component capacities, as listed in the Table 1. A statistical distribution is required for all these parameters, from which random values can be drawn. Note that the capacity for guy wires and conductors are defined as reliant on one parameter only; tensile strength found from tests. In reality, wire strength can depend on other factors, such as corrosion, anchoring in steel terminations etc. More governing parameters can be added if deemed necessary. Nonetheless, at present this is considered a reasonable level of detail.

Table 1: Dependency of input parameters for each component transmission line component, with references to choice of distributions

Component	Parameters required for capacity calculations
Steel beam:	*YS / TS (beam, bolt), E, λ, d,* d_0, e_1, e_2, p_1, p_2, *t*, TS_{cable}
Foundation concrete:	*YS / TS (rebar / bolt)*, ε_{max}, *d*, f_c, f_t, p_{rebar}, s_{soil}
Foundation soil:	ρ_{soil}, $\rho_{concrete}$, σ, φ, d_{gw}
Wire / conductor:	TS_{cable}

Governing parameters	Distribution references	Symbols
Yield / tensile strength – beam, bolt, rebar:	[2], [3]	*YS / TS*
Strain limit:	[4]	ε_{max}
Elastic modulus:	[2], [5]	E
Buckling curve:	[2], [6]	λ
Bolt / hole diameter:	[7]	d / d_0
Bolt end / edge distance:	[7]	e_1 / e_2
Bolt spacings:	[7]	p_1 / p_2
Thickness:	[6]	t
Cable strength (steel wire / conductor):	None (Test reports)	TS_{cable}
Concrete compressive / tensile strength:	[4]	f_c / f_t
Position of rebars:	None (Judgement)	p_{rebar}
Unit weight soil / concrete:	[8]	ρ_{soil} / $\rho_{concrete}$
Soil cohesion / friction angle:	[8]	σ / φ
Ground water level:	None (Project specific)	d_{gw}
Soil support on chimney:	None (Project specific)	s_{soil}

<u>Stochastic parameter values</u>

The distributions are defined such that each parameter represents all members of a tower or foundation. In other words, only one random draw is necessary per parameter per tower. For instance, steel yield strength is the same for all tower members, as is the increase / decrease in bolt hole end distance. Note also that only normal distributions are used today, but that this can be changed.

The current software version does not include time deterioration of the governing parameters. Hence, a parameter value is drawn once every defined lifetime, typically 10, 30, 50 years or similar, depending on the expected remaining life of an asset. Deterioration may, however, be included indirectly by defining a broader statistical distribution. The analysis should then be run for a long time, i.e. several orders of magnitude longer than the defined lifetime, such that the stages of deterioration are reasonably well covered in the input parameters.

<u>Governing codes</u>

The governing codes for steel, concrete and geotechnical capacities are EN 1993, EN 1992 and EN 50341-2-16, respectively. EN 1993 and 50341-2-16 are quite detailed in describing how capacities are calculated, whereas EN 1992 is somewhat more general. As a result, concrete capacity formulae are also based on other literature sources.

Tower response check

The methodology uses pre-calculated PLS Tower analysis results to create response surfaces, see [1]. This is founded on a linear tower response assumption, such that response from individual load components simply can be summed together. For a lattice tower this is a sound assumption. However, for Statnett's towers, which are internally guyed, this assumption must be verified. For Ørskog-Sykkylven, one tension tower and one suspension tower were evaluated, member by member. A reasonably good agreement was found, with deviations sometimes a little over 10%.

Multi-variate weather modelling

The weather model represents the long-term variability of all governing environmental variables, which for transmission lines in Norway are wind (speed and direction), air temperature and ice weight / thickness. At all defined locations, typically the tower locations, all parameters are modelled. An example is presented in Figure 1

As opposed to the approach presented in [1], where conditional distributions were used to maintain correlation, wind is now modelled by use of copulae. In addition, temperature is added as a parameter, which allows for a more physical ice modelling.

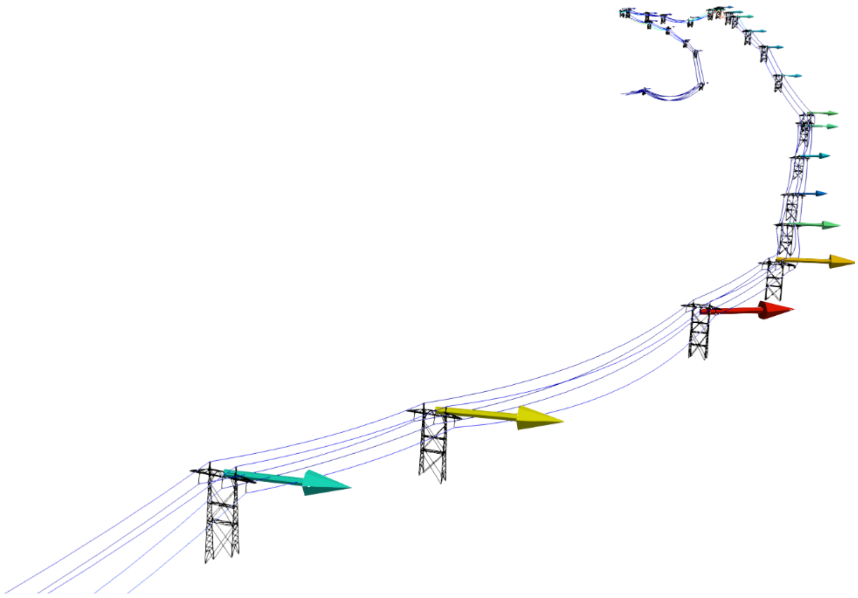


Figure 1: Illustration of transmission line. Each arrow represents a point in the statistical weather model where long-term statistics for wind, ice and air temperature is generated. Arrows represent wind.

<u>Wind speed, wind direction and temperature</u>

Temperature variations do not differ much from one tower to the next. There is usually a strong correlation. For wind speed and direction, however, the same is usually not true. Thus, spatial correlation can be quite complex to model, especially for a transmission line route with many towers. Care should be taken in choosing the copula to best describe the physics of a typical transmission line route.

Figure 2 illustrates a bi-variate distribution, showing wind speed and direction. Two dominant wind directions can be seen, where some wind directions are common for low wind speeds and others are more common for high wind speeds. The correlation between only these two variables is clearly non-linear.

A copula requires input on [0, 1], thus the "real-world" distributions are converted by the probability integral transform. The right side of Figure 2 presents the CDFs of the two variables, i.e. the distributions after the transform. It is in this domain, the probability domain, that a copula models all variables.

A conventional copula, such as the Gaussian, is not capable of representing the complex bi-variate distribution in Figure 2 properly. To best model the non-linearity, wind speed, wind direction and temperature have been fitted to an empirical Bernstein copula. The Bernstein copula represents the correlation observed in the hindcast data extremely well. However, one downside with the Bernstein copula is that it performs a numerical fit to hindcast data. This might in turn lead to overfitting, especially with short hindcast time series. Nonetheless, the benefits are considered to clearly outweigh the potential for overfitting. The Bernstein copula is implemented from OpenTURNS [9].

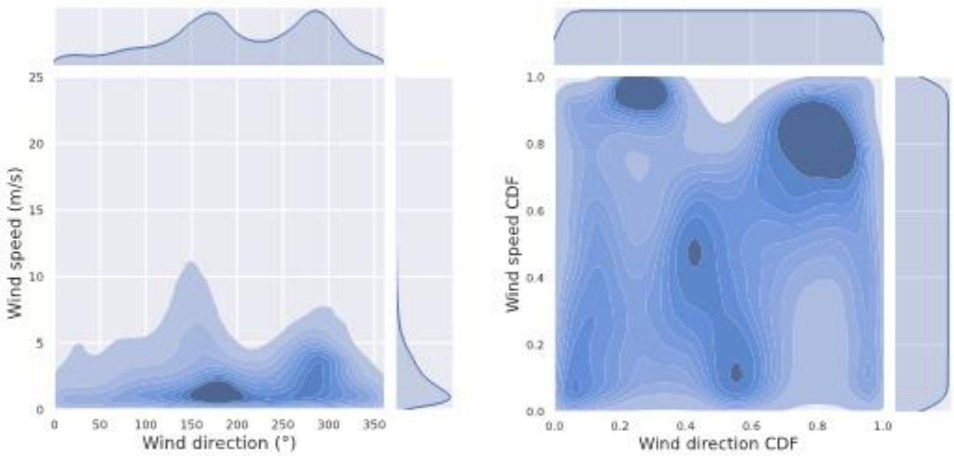


Figure 2. Left: Joint probability density distribution plot of wind speed [m/s] and wind direction [degrees] from hindcast data. Right: Corresponding joint cumulative distributions (CDF) of wind speed and wind direction. Both: Marginal distributions are displayed above and to the right of the coordinate axes.

<u>Ice model</u>

The basis for the ice model has not changed drastically from [1], however, rime ice with shedding has been included to the analysis model. Furthermore, both wet snow and rime ice modelling are now coupled with temperature, with wet snow generally occurring at temperatures around 0 degrees and rime ice at freezing temperatures.

Ice shedding introduces realistic skew loading events. It should be noted that ice shedding is only modelled for rime ice, as the statistical basis for wet snow events is not yet sufficient.

<u>Drawing sequence</u>

The complete drawing sequence for the weather modelling is presented in Figure 3.

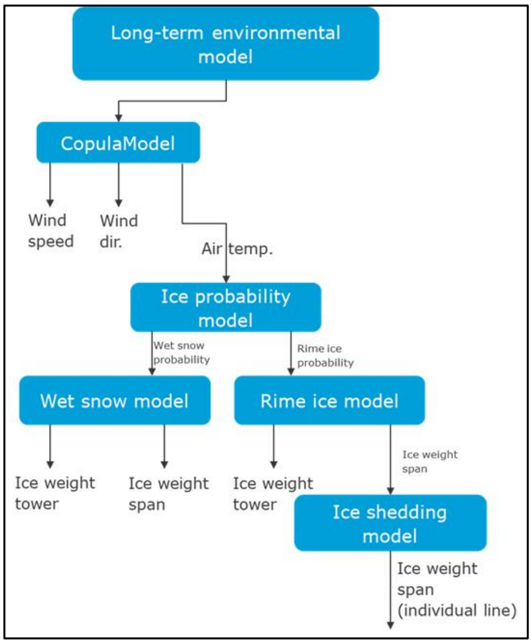


Figure 3: Complete drawing sequence of the stochastic weather model

Validation of weather model

The model is validated by statistical comparison of sampled model data to the hindcast data for the same location. Since generating realistic loading conditions on lines and towers is the primary objective of the environmental model, important behaviours to consider are:

- Distribution of maxima (especially the tail of the distribution where the extremes occur)
- Directional distribution, which may vary significantly over the length of the transmission line, due to variable topography and wind conditions
- Correlation between stochastic variables, which is of importance for the loads on the transmission lines
- Spatial correlation over several spans

All marginal distributions and correlation plots are evaluated as part of the quality assurance. A selection of these is presented below for a 15 tower long sub-section of Ørskog-Sykkylven.

Figure 4 presents 12 years of hourly wind speeds, obtained from both hindcast data and from weather model simulations, with particular focus on distribution tails. For all three locations, presented for wind speeds > 5 m/s, model and hindcast distributions match very well. Figure 5 presents wind direction density distributions at the same locations. The model seems well capable of capturing the governing wind directions, although these vary significantly over the transmission line length.

Figure 6 shows the resulting scatter plot between wind direction and wind speed for wind point "env point 1". Clearly the copula model reproduces the correlation of the hindcast data well, despite the correlation being very non-linear. To illustrate the spatial correlation, a scatter plot for wind speed at two different locations are plotted in Figure 7. Again, the copula model seems to reproduce the behaviour observed in the hindcast data quite well.

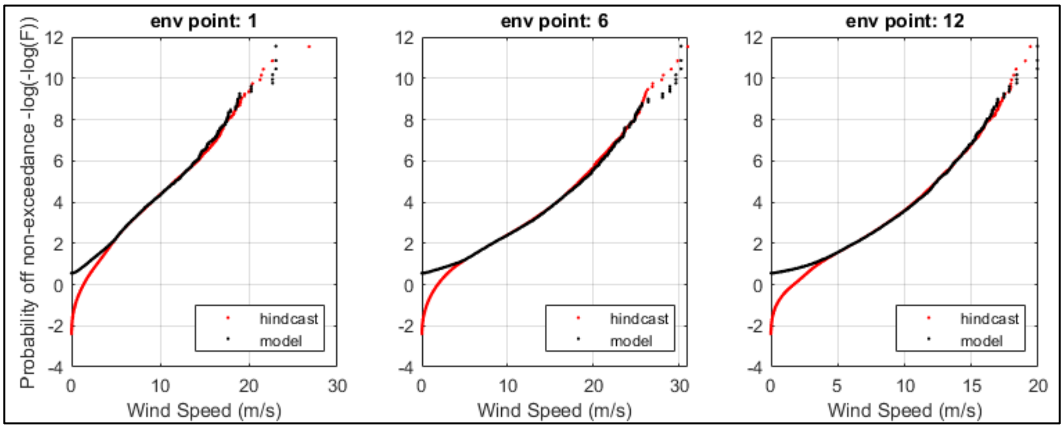


Figure 4: Gumbel plots comparing marginal wind speed distributions at three separate locations along the transmission line. Red dots: hindcast data. Black dots: model results.

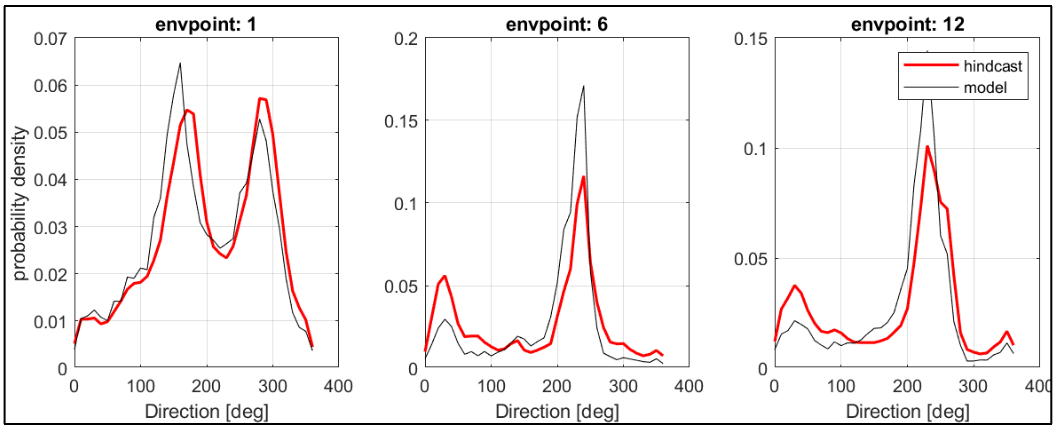


Figure 5: Probability density plots for wind direction for three separate locations along the transmission line. Red line: hindcast data. Black line: model results.

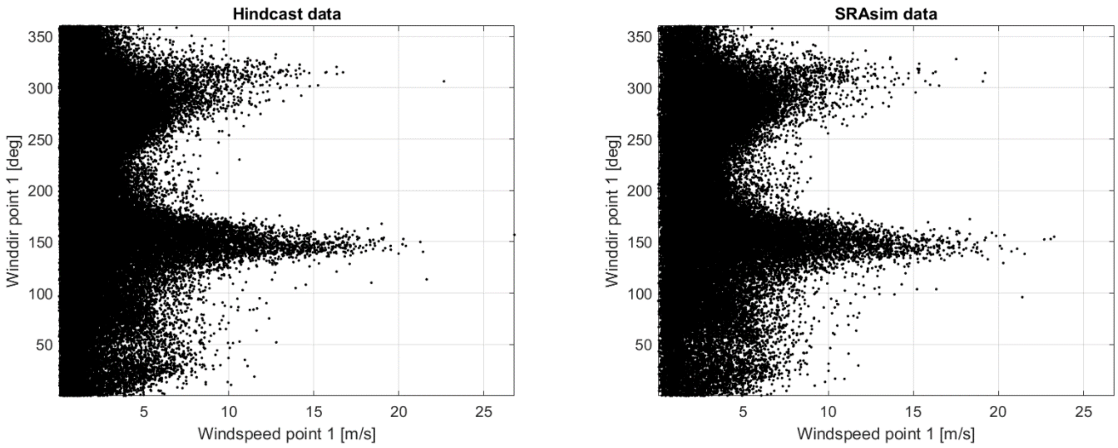


Figure 6: Scatter plot showing correlation between wind speed (x-axis) and wind direction (y-axis). Left: hindcast data. Right: model results.

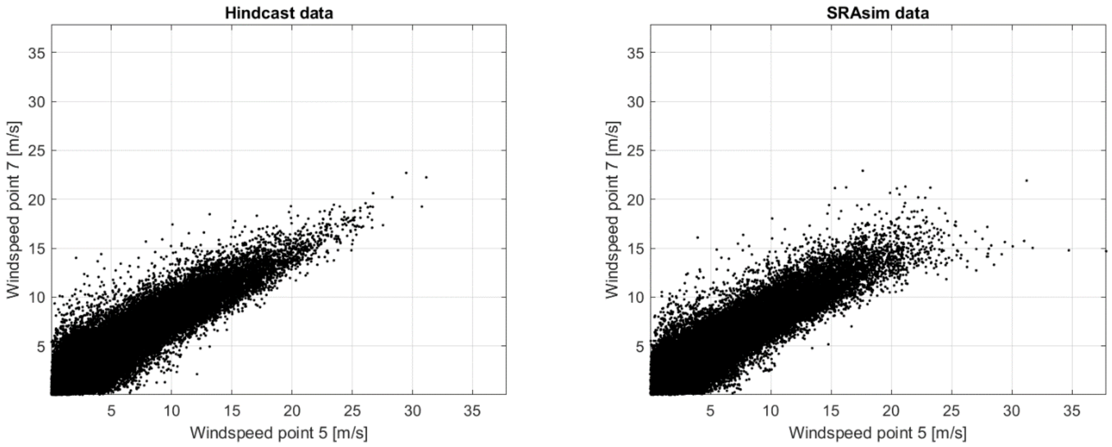


Figure 7: Scatter plot, illustrating the spatial correlation in wind speed between two locations. Left: hindcast data. Right: model results. The distance between wind points 5 and 7 is approximately 1 km.

Short-term weather modelling

While air temperature and ice can be considered constant over the sampling interval (1 hour), wind turbulence will generate short-term fluctuations of wind loads over the length of the span. A short-term wind model was therefore implemented to generate a three-variate turbulent wind field (u, v, w components) time-series of fluctuating wind. The implemented model is based on Fast Fourier Transforms (FFT) to generate wind time-series, by using a Kaimal wind spectrum [10], [11] and the Davenport coherence model [12].

Results

Ørskog-Sykkylven

This line route was investigated in [1]. However, due to major upgrades to the methodology it has been reanalysed. The major upgrades and their expected effects are listed in Table 2.

Table 2: Methodology upgrades and expected effects

Change	*Expected effect*
Improved weather modelling, better description of correlation	Increased maximum loading due to more spans loaded simultaneously
Line rupture	Increased tower loading if line breaks
Statistical capacity modelling	Increased capacity due to use of non-conservative input

A deterministic comparison of tower failures is not possible due to the nature of Monte-Carlo analyses. However, a statistical comparison can be made, especially if the differences are clear. Figure 8 presents three sets of results, all based on 50 000 years of analyses:

1. Analysis with updated methodology (upper left)
2. Analysis from [1] (upper right, red background)
3. Analysis as in 1., but with all capacities reduced to 80%.

TowerID	Number of failures in simulation	Number of annual failures	Number of design life failures	Annual failure probability	Design life failure probability	Return period of annual failure
Route	1	1	1	0.00002	0.001	50000
18	0	0	0			
19	0	0	0			
20	0	0	0			
21	0	0	0			
22	1	1	1	0.00002	0.001	50000
23	0	0	0			
24	0	0	0			
25	0	0	0			
26	0	0	0			
27	0	0	0			
28	0	0	0			

TowerID	Number of failures in simulation	Number of annual failures	Number of design life failures	Annual failure probability	Design life failure probability	Return period of annual failure
Route	117	117	114	0.00234	0.114	427
18	1	1	1			
19	0	0	0			
20	0	0	0			
21	0	0	0			
22	35	35	33	0.0007	0.033	1429
23	81	81	80	0.00162	0.08	617
24	0	0	0			
25	0	0	0			
26	0	0	0			
27	0	0	0			
28	0	0	0			

Capacity of all members reduced to 80%:

TowerID	Number of failures in simulation	Number of annual failures	Number of design life failures	Annual failure probability	Design life failure probability	Return period of annual failure
Route	40	40	8	0.0008	0.010	1250
18	0	0	0			
19	0	0	0			
20	0	0	0			
21	0	0	0			
22	40	40	8	0.0008	0.010	1250
23	0	0	0			
24	0	0	0			
25	0	0	0			
26	0	0	0			
27	0	0	0			
28	0	0	0			

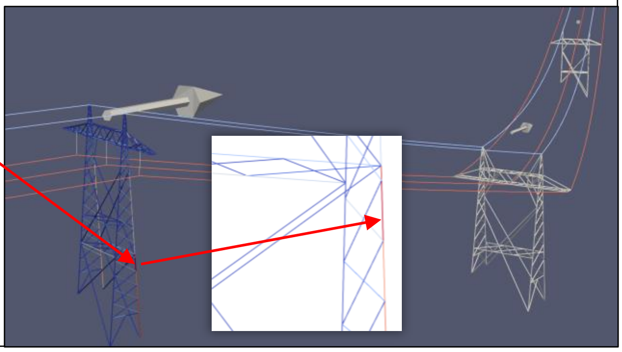


Figure 8: Analysis results after 50 000 years of simulation – Ørskog Sykkylven

The old methodology was clearly more conservative for this line route. If the capacity of all towers is reduced to 80% tower 22 exhibits a more similar failure rate. Note that no failures are observed for tower 23, which was the most critical in [1]. This may stem to some degree from a change in capacity. However, the main cause is most likely due to modelled loads on tower 23 having changed with the updated weather model. No line ruptures were observed.

<u>Sima-Samnanger</u>

The Sima-Samnanger line, which runs through the Aalvik mountain area, was energized in 2013. Within one year of operation the earth wire peak of tower 169 failed. Roughly 50 kg/m of ice load due to rime ice was measured during the failure investigation, much more than the towers were designed to support. As a consequence, Statnett has set up a test span next to towers 169 and 170, which were thought to be the most exposed to icing events. During 5 to 6 years of measurements very large ice loadings have been recorded in the test span; nearly 50 kg/m one year, and nearly 80 kg/m in another. In addition, the earth wire was removed for towers 163 – 180. There have been no more mechanical failures since, except for an insulator attachment.

40 years of hindcast data has since been produced with high resolution. This has been compared with simulated weather data, as presented in Figure 9 for several of the most highly loaded towers. Some data points up to 200 kg/m can be seen for towers 169 and 170, and many above 100 kg/m. This suggests that frequent failures are to be expected. Indeed, a ProTECT simulation was run for 128 years for all 30 towers, which shows a very high failure probability, see Table 3. This is in accordance with hindcast data, but not with experience from the last 5 to 6 years. A probable cause of this discrepancy is that after a high icing event, Statnett will act to remove the ice, especially since heavy icing also leads to electrical faults. This means that very long-lasting ice accumulation events, up to and above a month, are highly unlikely. The mitigating measures should be included in the weather modelling, which in turn will reduce simulated icing loads on the towers and lines to more realistic values. However, long icing events without opportunities to remove the ice will still lead to high ice loading, albeit not as extreme.

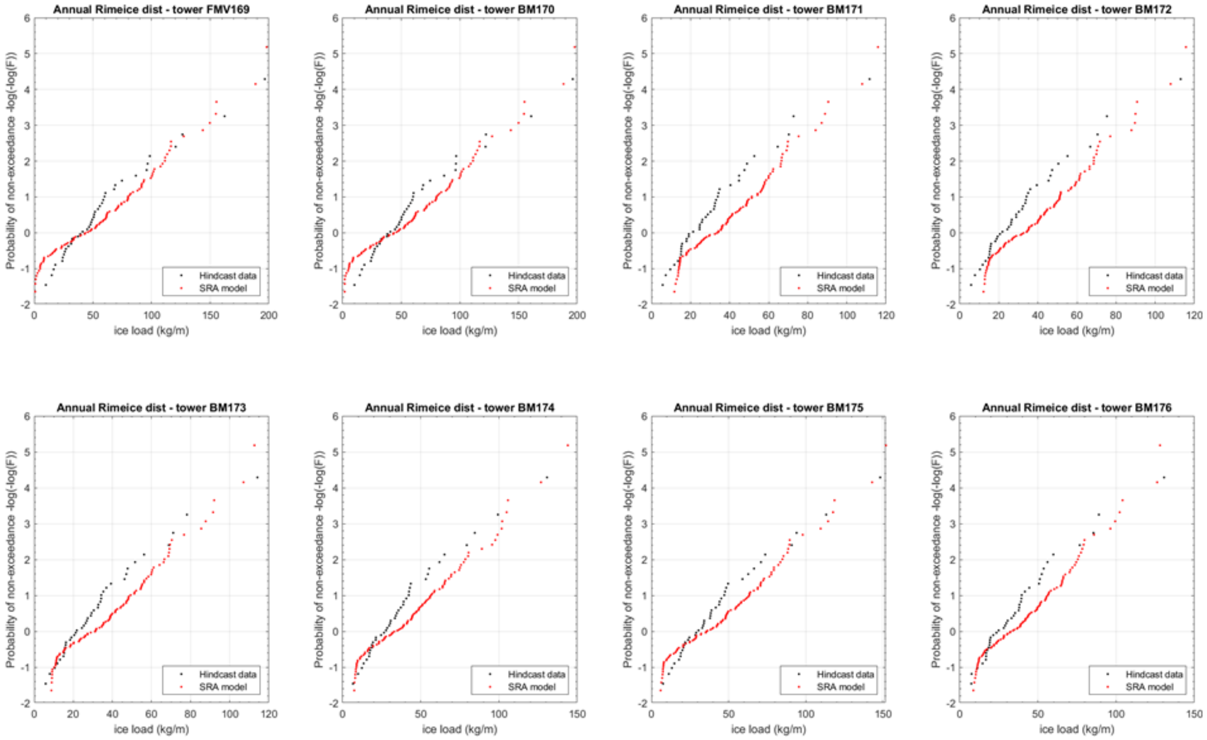
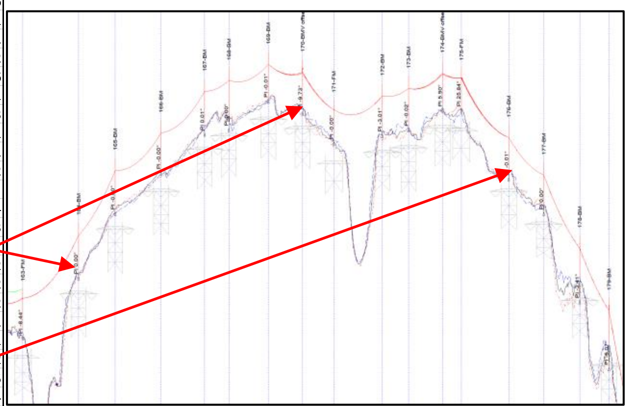


Figure 9: Annual rime ice distributions at Sima-Samnanger, for the towers most exposed to rime ice. Black dots: hindcast data Red dots: model results. One dot signifies the highest ice load in one particular year.

Table 3: Analysis results after 128 years of simulation – Sima-Samnanger

TowerID	Number of failures in simulation	Number of annual failures	Number of design life failures	Annual failure probability	Design life failure probability	Return period of annual failure
Trasé	10915	117	3	0.91	1.500	1
152-fm	42	20	3	0.16	1.50	6
153-bm	14	8	3	0.06	1.50	16
154-bm	14	6	3	0.05	1.50	21
155-bm	28	12	3	0.09	1.50	11
156-bm	18	11	3	0.09	1.50	12
157-bm	12	5	3	0.04	1.50	26
158-bmv	16	6	3	0.05	1.50	21
159-bm	8	3	2	0.02	1.00	43
160-bm	16	6	3	0.05	1.50	21
161-bm	9	6	3	0.05	1.50	21
162-bm	10	4	3	0.03	1.50	32
163-fm	0	0	0			
164-bm	3228	29	2	0.23	1.00	4
165-bm	297	48	3	0.38	1.50	3
166-bm	637	57	3	0.45	1.50	2
167-bm	1223	66	3	0.52	1.50	2
168-bm	1765	72	3	0.56	1.50	2
169-bm	2826	79	3	0.62	1.50	2
170-bmv	3297	90	3	0.70	1.50	1
171-fm	2943	92	3	0.72	1.50	1
172-bm	5629	53	3	0.41	1.50	2
173-bm	442	27	3	0.21	1.50	5
174-bmv	384	36	3	0.28	1.50	4
175-fm	2907	97	3	0.76	1.50	1
176-bm	843	59	3	0.46	1.50	2
177-bm	154	42	3	0.33	1.50	3
178-bm	0	0	0			
179-bm	0	0	0			
180-fm	6	5	3	0.04	1.50	26
181-fm	1	1	1	0.01	1	128



Conclusive remarks

The methodology is now mature enough to use for existing lines. It is possible to make use of the state of the structures, by use of capacity distributions, in addition to modelling weather accurately for the desired design life. However, examples such as Sima-Samnanger show why experience and measurements are important, and that analysis results should always be compared with real-world experience for a transmission line. This will continuously gain confidence in the ProTECT tool.

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