Online Reliability Calculations of Power Systems with Forecasted and Real Time Weather Influence

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ABSTRACT: Goodtech Power and Statnett SF have developed an online regularity calculator with minimal delay between acquisition of process values and presentation of regularity indices for the power grid. The simulation tool calculates the probability of failure on every component in the system, and combined with a flow model, the reliability of power supply for every load branch.

This paper discusses online reliability calculations and the importance of including weather data in such calculations. The paper discusses necessary statistical data and how to derive weather dependent correction factors from these data. The methodology discussed in this paper has been developed in a research collaboration between Goodtech Power and StormGeo.

1 INTRODUCTION

The fascinating, but very complex field concerning reliability analysis of power systems was opened by J. Endrenyi in his excellent textbook (Endrenyi, 1978) and later expanded by R. Billinton and R. N. Allan in their textbooks (Billinton, 1983) and (Billinton, 1996). Both these pioneers pointed out the efficiency of Markov models. However, lack of efficient tools for building large Markov models restricted practical application of this method and several publications have argued, incorrectly, that Markov models was not applicable in practical applications.

In a master's thesis carried out by Arne Brufladt Svendsen (Svendsen, 2002), thesis advisor Tørris Digernes discovered a method suitable for building large Markov models. A central clue in the calculation was the Kronecker matrix operators, (Sasty, 1999). The method was tested by Svendsen in his thesis and found to be very efficient for reliability analysis of power systems. Since then, various R&D projects concerning offline calculations of reliability of supply in complex meshed power grids have been carried out.

Although Promaps, a simulation program used to evaluate risk of system failures in power systems, was designed for offline analysis, it was early recognized that the concept also was suitable for online analysis. In 2009 an agreement between Goodtech Power and Statnett SF in Norway was signed concerning development of a computer program for online calculation of reliability of supply in the Norwegian main electrical power grid. The project was put in online operation October 2013 in Statnett's operational central.

Most reliability assessments use fault statistics that averages the number of fault contingencies over the year. This statistics makes double or triple fault contingencies highly improbable, and thus the impacts of such contingencies are often disregarded. But few faults in the power grid occur on an average day with average weather conditions. Extreme weather conditions can affect large areas and will significantly increase the probability of faults, and thus making double contingencies much more probable.

Goodtech Power and StormGeo collaborated in a preliminary R&D project through 2013-2014. The goal of the project was to look at reliability assessments sensitivity to weather parameters, and develop methodology to include such effects in Promaps.

This document contains a presentation of the online risk tool Promaps Online, currently running simulation of the Norwegian power system. Furthermore in this paper we present the results from that preliminary project in 2014, and how these results will be used further.

Section 2 presents the needs as seen from the grid owner's point of view. Section 3 presents the principles and background behind the reliability calculations. Section 4 describes how results are presented today. Section 5 describes the data used as input for this project. Section 6 gives an analysis of the data and results. The conclusions are presented in section 7.

2 THE TSO POINT OF VIEW

The Transmission System Operator (TSO) is faced with increasing requirements regarding the reliability of power delivery. The cost of not delivering agreed energy can be substantial.
In Norway there is a cost (CENS) connected to energy not being delivered. If a grid company has low continuity of supply, the company will experience a reduction in the allowed network charges every consumer pays.

The most important tools for power system operators are power flow calculations, dynamic analyses etc. To analyze the reliability of supply, additional tools are needed.

2.1 *Calculation tool*

It is easy for a TSO to recognize the need for simulation tools that can calculate the risk levels for different time horizons. Such a simulation tool should be useful for a TSO in online operations, day-ahead and intraday short-term grid planning:

Online operation:

- In online operation the risk level is calculated every minute and evaluated if risk indices are out of boundary or out of planed and accepted risk level for the coming hours.

Day-ahead and intraday-planning:

- Short time planning of operation to perform detailed simulations for the next days based on planned power system parameters and grid configuration.

2.2 *Importance of weather data*

With the new reliability calculation tools entering the industry, TSOs are for the first time able to get detailed information about the state of the power system every 10 minutes. This makes it easier for the operator of a grid to make decisions on how to minimize risk levels.

However, if those tools do not take into account important factors as wind and thunderstorms, the operators still have to make personal judgments on how weather affects the situation. For efficient decision making in the control room, it is important to minimize the amount of extra information the operator has to include when interpreting the results.

3 ONLINE RELIABILITY CALCULATIONS

Online calculations in Promaps consist of the following steps:

- Data acquisition
- Calculate probability and frequency of branch failure in power grid
- Calculate probability and frequency of all contingencies, and select a subset of contingencies with the highest probability of occurring
- Calculate consequences of the contingencies selected in previous step.
- Calculated aggregated risk indices based on probability and consequences of all selected contingencies
- Present results for users

These steps are then repeated every ten minutes, as new data is available, thus enabling trending of risk indices. A closer description of each step follows:

3.1 *Data acquisition*

Data acquisition requires that Promaps is integrated in the TSO's SCADA-system. Necessary data are: an electric model of the power grid, process values, switch positions, information about protection schemes, and information about available spinning reserves. During online calculations only process data, switch positions and spinning reserves are necessary to calculate and update the risk indices.

3.2 *Branch reliability*

Probability and frequency of branch failures are calculated by compositing Markov models and aggregation of states. Promaps represents each component, related to power flow properties, with a Markov model. Each model describes possible states of the component and frequency of transition between states. Examples of states can be "functioning normal", "temporary error" and "sustained error". Markov models representing each branch in the power grid are then created through compositing models of all relevant components, and aggregating all resulting states with similar net effect on the power system. This enables Promaps to model every individual component in the power grid, thus making use of all available failure statistics. The full explanation of this methodology was presented in (Digernes, 2004).

3.3 *Grid reliability*

A contingency consists of one or more branches failing at the same time. For a large power grid, the number of possible contingencies is infinite for all practical purposes. Therefore, consequence evaluation of all possible contingencies is not possible. Instead, Promaps calculates the probability of each contingency occurring, and select a subset of contingencies based on the probability. This subset typically consists of thousands of contingencies, but will usually cover close to 99% of the complete probability space.

3.4 *Consequences of contingencies*

Each contingency has to be evaluated for consequences for the power grid. Consequences of interest are reduced ability of delivering power to load points. Promaps uses an economical load flow model, where different costs are assigned to production and spinning reserves, and load shedding are prioritized according to cost of not delivering energy. The methodology also supports different kinds of system protections.

3.5 *Aggregated risk*

Risk of the system not being able to deliver required energy to each load point can be calculated based on probability, expected frequency and consequences of all consistencies. Several risk indices can be derived from these results, the main risk index calculated in Promaps being *system minutes*, SMS. System minutes are the expected energy shortage normalized on the size of the power grid.

3.6 *Presentation of results*

In the end the results are presented graphically to the users. Promaps has based its graphical view on TSOs SCADA pictures, adding a layer of risk indices.

To be able to quickly asses a power system's risk level, few key risk parameters should be presented. In Norway there is a cost for energy not being delivered to the customer (CENS). This cost is divided into different customer groups and time of day. When a TSO experience a loss of load, the TSO will get a reduction in next year income based on outage and the corresponding CENS cost.

The Promaps simulation tool calculates the power delivery reliability as a function of demand, the probability for undelivered energy for each load branch in the system and for the system as a whole. Therefore the CENS cost factor could easily be included in the results and are currently one of the system risk indicators used. In addition not delivered energy and corresponding CENS cost, system minutes (SMS) is used as an online risk indicator.

Currently the SMS index is being used to set the limits for the dynamic color indication for the risk level in the system. In the test evaluation phase that is ongoing, the following level is set for the total system minute (SMS):

- 0-10 minutes, no color
- 10-15 minutes, yellow color
- >15 minutes, red color

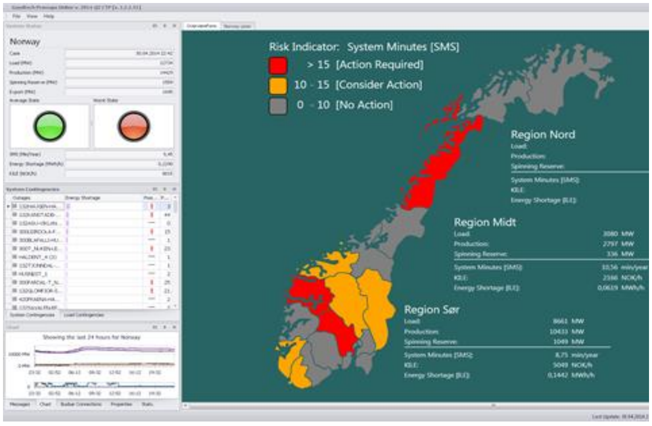

Figure 1: Overview of the risk level in each region

The color indication is shown on a regional level in Figure 1. The colors represent the expected energy shortage normalized of the size of the respective region.

The color indication is shown on the single line diagram of Figure 2 for each load branch and for the total system. If there is yellow risk indication for the system the operator should evaluate possible action to be taken if the risk level further increases. If the system experience red indication the operator shall perform a power system action to reduce the risk.

Figure 2: The standard operational view for one region

The schematics in Figure 2, is based on the schematics currently being used by the TSOs in their operational central.

4 INCLUDING WEATHER PARAMETERS IN RISK CALCULATIONS

4.1 *Empirical data*

The project started with gathering data about historical faults in the Norwegian power grid and weather conditions when the fault occurred. Necessary fault parameters were fault type, geographical location and point in time.

All contingencies in the Norwegian power grid are registered in FASIT. FASIT is a Norwegian coalition between grid companies, production companies and Norwegian water resource and energy directorate (NVE). The aim of the coalition is to register all faults, develop good statistics of power system failures, and develop a good national understanding of contingencies hazards in the Norwegian power grids.

This project acquired all error reports from FASIT in the period from 1998 to 2012. In this period there were registered 2128 contingencies related to power lines at 132 kV or more. Of these, 87.5 % were caused by environmental factors. These contingencies can further be broken into the following categories:

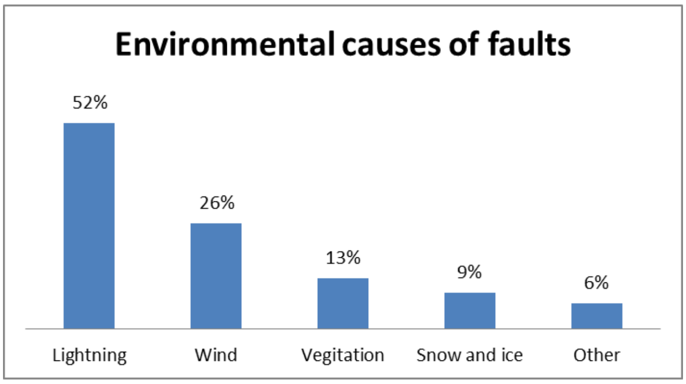

Figure 3: Break down of environmental causes

These error reports did however not include geographical coordinates of where the fault occurred, only description of the power line. Geographical coordinates of all substations were provided by Statnett. Location of the error was assumed to be halfway between both end-stations.

The historical weather data used in this study is generated by running a numerical weather prediction model on a grid covering northern Europe with 6 km resolution over a period of 33 years.
The Weather Research and Forecasting (WRF) Model is a next-generation mesoscale numerical weather prediction system designed to serve both atmospheric research and operational forecasting needs.

The WRF is a limited area model and to run the hindcast, re-analysis data from ECMWF has been used as boundary conditions. The model stores data every hour which means that all weather variables are available in each grid point for every hour over a 33 year period. As a companion to this hindcast, a forecast is run twice a day, 72 hours ahead with WRF configured exactly like in the hindcast. Extremes in the forecast can consequently be put into a 33 year context which makes this setup rather unique.

4.2 *Analysis of data*

In 2006 there were registered 72 contingencies on power lines (132 kV to 420 kV) caused by strong winds in Norway. That makes an average of 0.20 faults per day. But as illustrated in figure below, 63 of those 72 faults happened within 5 days, averaging 11 faults per day in that period. Considering that most of these errors probably occur in the same area, consequences of double contingencies should be taken into consideration. Average statistics has little relevance for scenarios when there actual is a risk for double or tipple contingencies.

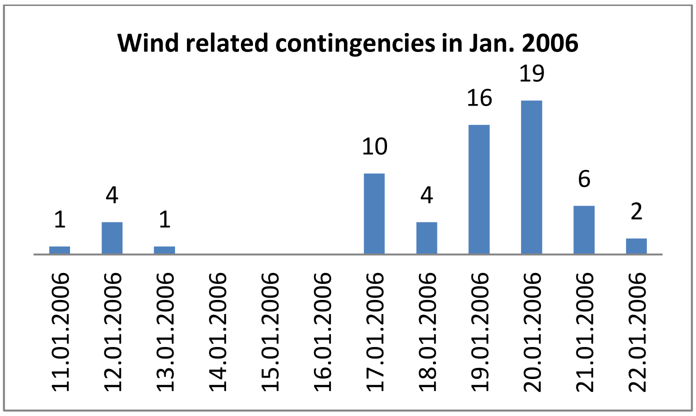

Figure 4: Reported power line faults per day in 2006 in Norway

As can be seen from the breakdown of historical data, lightning strikes and wind are the two most frequent causes of contingencies at power lines. This statistics can be used to break down the failure rate of power line into several terms:

$$\lambda = \lambda_{lightning} + \lambda_{wind} + \lambda_{other}$$

The total fault rate, λ, is known from yearly statistics. The aim of this project was to put numbers on the terms $\lambda_{lightning}$, λ_{wind}, and λ_{other}, and to adjust the weather related terms based on weather conditions. Based on the amount of available data, the project decided to focus on faults caused by wind. Wind is credited as the cause of 26 % of all environmental caused faults of Norwegian power lines.

Norway has a diverse landscape, ranging from coastal areas with strong winds from the North Sea, to wooded inland areas shielded from ocean winds by mountains. It has been assumed in this project that power grids in different types of landscapes have different tolerance for strong winds. This assumption is based on the logical conclusion from two other assumptions:

- More effort is put into preventing errors from winds in areas often subjected to heavy winds. For example are trees cut back from the power lines in wooded areas with strong winds, and there is more effort invested in removing ice from power lines
- Larger faults, like trees toppling on the power line, does not happened more often, as such instances likely already have occurred. Trees do not grow big in areas with strong winds.

Thus it is of more interest to know how fault rates change when wind speeds deviate from historic wind speeds in that area. This project normalized all wind speeds with the 99th percentile wind speed in the area (from now w99p as short). Thus ending up with eight categories:

- 0.0 – 0.2 of w99p
- 0.2 – 0.4 of w99p
- 0.4 – 0.6 of w99p
- 0.6 – 0.8 of w99p
- 0.8 – 1.0 of w99p
- 1.0 – 1.2 of w99p
- 1.2 – 1.4 of w99p
- 1.4 – 1.6 of w99p

All historic faults caused by wind were compared to wind speeds in that area at the time of the fault and assigned to one of these categories. The resulting distribution of wind speeds emerged:

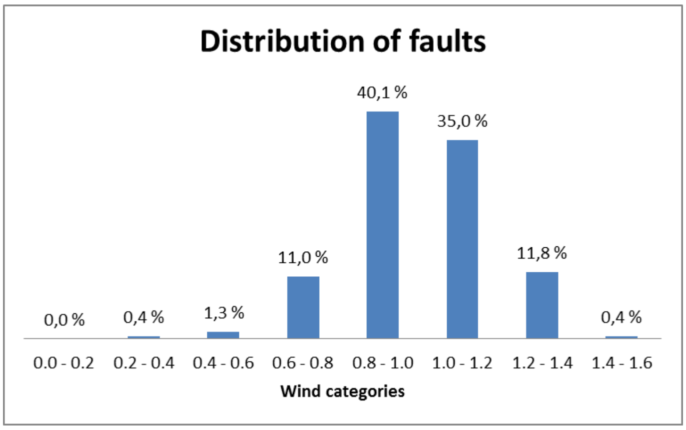

Figure 5: Distribution of faults to wind categories

These results show that most wind related faults happened in wind categories close to p99 (1.0 ± 0.2). This is as expected. But to say anything about the fault rate at different wind categories, distribution of wind have to be taken in to account.

The actual distribution of wind was not possible to disclose in this article, so instead fictitious values will be used to demonstrate the methodology. Given the following distribution of wind:

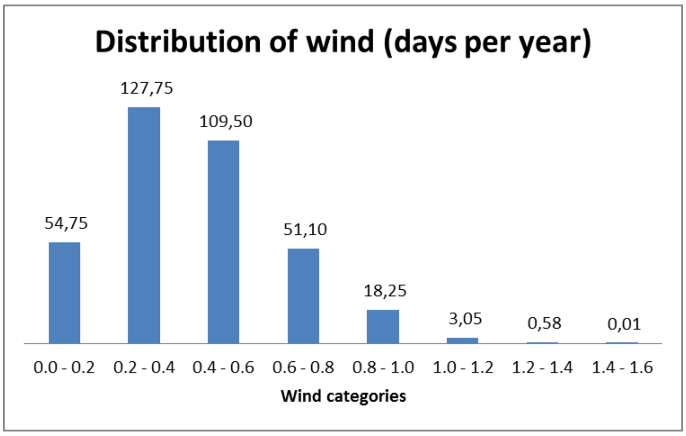

Figure 6: Distribution of wind categories

For each wind categories, a correction factor can be calculated by dividing the percentage of errors related to that category (Figure 5) by the percentage of time spent in that category (Figure 6). Or as follows:

$$c_{wind} = p_{faults}/p_{time}$$

where

p_{faults}	Percentage of fault occurring in category
p_{time}	Percentage of time in wind category

Performing this calculation for all wind categories results in the following set of correction factors:

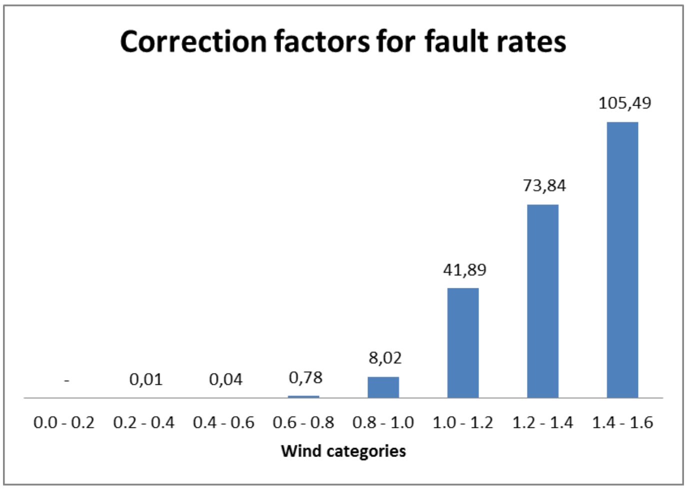

Figure 7: Wind dependent correction factors

All wind dependent correction factors are presented in the figure above.

4.3 *Including weather conditions in Promaps Methodology*

A new module can be implemented to include these results in Promaps. This module will import weather data and calculate fault rates live for each power line by the following formula:

$$\lambda = \lambda_{lightning} + c_{wind}\,\lambda_{wind} + \lambda_{other}$$

where c_{wind} is dependent on the latest weather data from the area the power line is located.

5 CONCLUSIONS

After installing the new simulation tool for reliability studies at Statnett SF, the need to support weather data has become prominent.

Goodtech and StormGeo launched a project to address this challenge, and came up with a system to include weather dependent fault rates in online reliability studies. The results from this project show, as expected, a strong correlation between faults on power lines and wind strengths. Through this project Goodtech and StormGeo have been able to put numbers on this correlation, and devised a system to include these values in Promaps calculations. This system uses correction factors to manipulate error rates dependent on current weather.

This system is also applicable for other weather phenomena. Goodtech and StormGeo has already continued this work and is now working on deriving similar correction factors related to lightning storms.

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