Online reliability assessment of power system

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Abstract — **TSOs have a responsibility to supply industry and communities with reliable electric power. However, the operators are virtually blind to slowly occurring changes in the load profile that reduce the expected regularity of the power supply. They also lack tools to assess various possible actions with respect to the expected regularity of power supply. As a solution to this problem, Goodtech Project & Services and Statnett SF have developed an online regularity calculator, with minimal delay between acquisition of process values and presentation of calculated regularity indices for the power grid. This makes it possible to abandon the conservative N-1 criteria, and instead operate according to a policy for maximum risk level or to a policy where focus is minimizing the total cost. The analysis method previous presented is using a method developed by Tørris Digernes MathConsult. The method is based on unit Markov component models build together to complete system models by Kronecker products and the states are reduced by aggregation of similar states. The power delivery ability is calculated by minimizing an object function with constraints concerning power balance and operation limits. This paper describes a methodology for online risk assessment calculation that is currently being tested. Calculations like this can be the start of changing current practice concerning the conservative N-1 criteria, to operation of power system by evaluating if the current risk level is within acceptable levels at any given time.**

***Keywords*- Online risk management; Challenge N-1; Markov unit models; Kronecker product**

I. INTRODUCTION

The fascinating but very complex field concerning reliability analysis of power systems was open by J. Endrenyi by his excellent textbook (Endrenyi, J. 1978) and later expanded by R. Billinton and R. N. Allan in their textbooks (Billinton, R. Allan, R.N. 1983) and (Billinton, R. Allan, R.N. 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 has argued incorrectly that Markov models was not applicable in practical applications.

As responsible for electrical power supply in TSO BKK Norway, Yngve Aabø experienced the need for new reliability calculation tools. This need resulted in a master thesis proposal which was carried out by Arne Brufladt Svendsen (A. B. Svendsen, 2002). Inspired by the pioneers Tørris Digernes, as thesis advisor, discovered a method suitable for building large Markov models. A central clue in this calculation was the Kronecker matrix operators, (Sasty S.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 delivery reliability in complex meshed power grids have been carried out. Responsible for the mathematical theory and the computer program kernel PROMAPS has been T. Digernes as owner of Tørris Digernes MathConsult. Responsible for power grid expertise and project implementation have been Y. Aabø and A. B. Svendsen as co-owners of Troll Power AS. Some of the projects have partly been financed by Innovasjon Norge. In 2010 Troll Power was incorporated in Goodtech.

Although PROMAPS was designed for offline analysis, it was early recognized that the concept also was suitable for online analysis and in 2008 an agreement between Goodtech Projects & Services and Statnett SF in Norway was signed concerning development of a computer program for on line calculation of delivery reliability in the Norwegian main electrical power grid. The project is now (end of 2011) about to be successfully completed. Method responsible has been T. Digernes. In Goodtech Projects & Services project responsible has been A. B. Svendsen, technical mentor has been Y. Aabø, and responsible for implementation has been J. Eman, and T. Tollefsen. In Statnett project responsible has been S. Løvlund and J.O. Gjerde has been creative concept adviser and is recently appointed as research director in Statnett SF in Norway.

This document contains a presentation of the project. Section II presents the needs as seen from the grid owner's point of view. Section III present the Statnett R&D project and the principle behind the on line calculations. Section IV describes the theoretical basis. And finally section V contains a discussion of results and experience from the project. Note that Section IV is with purpose put after Section III since our main focus is presentation of the results from the Statnett R&D project.

II. TSO POINT OF VIEW

A. Background

So far, the most important principle of transmission network reliability in Europe is to guarantee (N-1) security, stringently and transparently. This criterion aims at ensuring the survival of the electric power system after the occurrence of a single contingency for any of its critical elements, e.g. overhead lines, cables, transformers, capacitors, generation units, HVDC lines, phase shifters, etc. The loss of any single primary component must not cause any loss of load, instabilities or cascading phenomena. This criterion assumes that the probability of such a single contingency is one order of magnitude higher than the joint probability of all other two or more simultaneous (independent) contingencies. It also requires that each TSO operates its own system so as to avoid that any cascading effect within its "own" grid impacts any of its neighbors.

The present project focuses on defining transition paths which will allow TSOs to move from the stringent use of the N-1 rule to a new Comprehensive Reliability Methodology (CRM) which allows for the management of system uncertainties in a more integrated and cost-effective way, over all time horizons.

B. *Why moving away from the present N-1 rule?*

Present practice consists in identifying the worst operating conditions for each particular time horizon, by performing an N-1 analysis of such situations, and taking actions for avoiding the foreseen consequences:

- In the long run by investing in new infrastructures or in market mechanisms
- In the medium run by limiting the market parties in planning outages and in exchanging energy
- In the short run by cancelling maintenance activities and implementing re-dispatching measures.

However, the bigger the uncertainties, the fuzzier the worst operating conditions (or situations). As uncertainty levels increase, current practice struggles in evaluating the right contingency which follows less and less the well-known N-1 rule, but starts also including deviations from the studied situation to embrace these rising uncertainties. Hence critical situations become bad combinations of many different factors including cascades and unexpected sequences of failures in the countermeasures. The N-1 rule is contingency-based in the sense that an event is an unplanned outage. The future CRM must focus on the situation (be situation-based) to fully address the main issue: growing uncertainties.

C. *The TSO's need*

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 indexes are out of boundary or out of planed and accepted risk level for the coming hours.

Week-ahead planning:

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

III. ONLINE RISK SIMULATION

A. *Background*

The scope of work (SoW) in the Statnett R&D project was to develop a reliability simulator for short time planning of operation and in online operation of the power system. The idea behind the SoW was to create at tool that formed a base for operation division, and create a common understanding of the influence of risk in division.

B. *Project goal*

The goal for the simulation tool is for short time planning of operation to perform detailed simulations for the next hours based on planned power system parameters and grid configuration. The simulation results are then included in a one page risk report, and handed to the control central operator before the next working shift.

The risk report will act as a risk forecast for the coming hours. The risk forecast will present key power system data and key risk indicators. In addition to the risk indicators, the risk report will present a risk contingency list of the 10 most influencing fault contributors, and a list with possible actions to solve the risk contingency list problems if they occur.

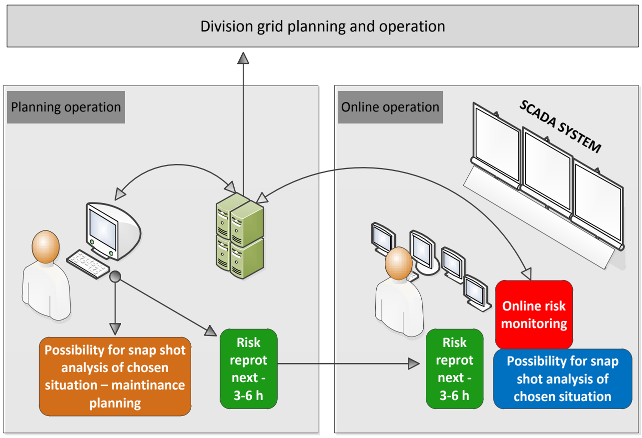

Figure 1. Planned work process for risk based operation of power system

C. *Methodology*

The methodology used in the project was based on the previous presented theory and principle from [PMAPS 2004]. The methodology use small Markov unit models to represent each component in each branch in the power system, by applying the Kronecker product operator, the reliability state space for all components in the branch can be calculated. The same principle is then used for combing all branches in the system when combined with advance aggregation technique. The reliability methodology is combined with a flow model based on optimization technique. The calculation principal is described in chapter IV.

D. *R&D challenges*

The reliability simulator was first developed and implemented in MATLAB. MATLAB is very suitable when developing software tool for solving mathematical methods containing large matrices and matrix operations. However when the first tests and verifications were done and a method was approved the project decided to change software platform. What was gained in user-friendliness when writing algorithms is lost in memory handling and difficulties to make the software scalable.

1) Calculation speed and model size

In order to increase the calculation speed the most time consuming operations were identified. The routine for identifying fault states which should be analyzed further were optimized and rewritten.

Running the QP-solver was found to be the most time consuming part of the calculaitons. The next step was to find a more efficient QP-solver since the routine in MATLAB's optimization package. In order to evaluate different external QP-solvers a fictive model was built combining eight copies of the power grid from the original model supplied from Statnett SF comprising a total of 952 branches and 328 nodes (busbars).

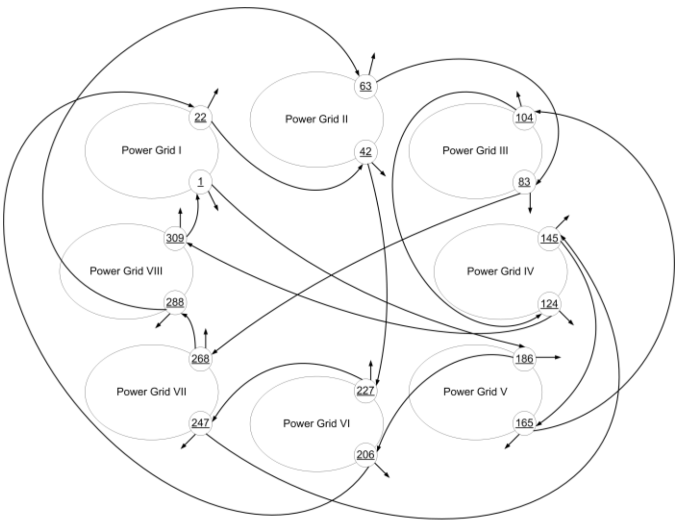

Figure 2. Test of a large power system

Tests show that supported with the fastest QP-solver the reliability software solve this fictive model in 17,2 seconds. This can be compared to the original QP-solver that used more than one hour to solve a test combining to power grid, i.e. 25 % the size of the final test model.

2) Data infrastructure arcitecture

In order to make the reliability software scalable and easier to distribute to customers, first during evaluation and developing but later on as a software product, it has been implemented in a whole new architecture and rewritten in C# in a .NET environment.

All online data from customer are parsed through a gateway to get the "right" form and to be combined with the previous stored model and static data. A calculation administration service (CAS) distribute calculation packages through a message system to first be calculated in a calculation service (CS) and then to client(s) for presentation.

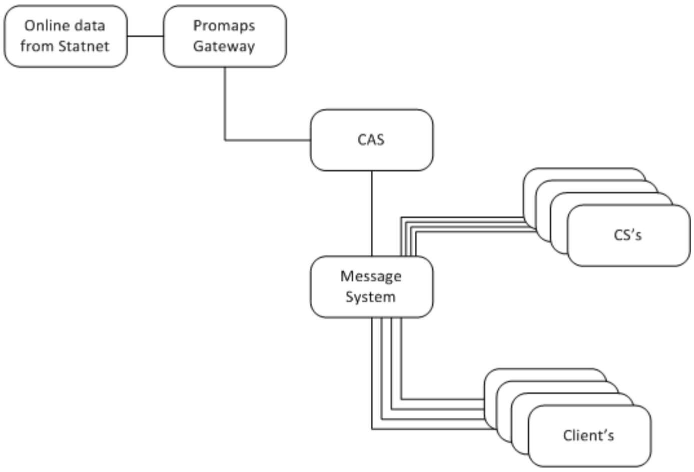

Figure 3. Data infrastructure arcitecture

This architecture allows many users to subscribe to online calculations performed on a central server, hence each calculations has only to be performed once and the individual user has just to install a light weighted client that can receive data. Furthermore the calculation administration service is not limited to just one calculation service. In case of a user wants to simulate a modified snapshot, the snapshot is send through the message system and can be calculated on a separate calculations service in order not to interfere with the regular online calculations.

E. Risk indices and presentation of result

To be able to fast asses a power systems risk level, few key risk parameters should be presented. In Norway there is a cost for not delivered energy to customer (KILE cost). This cost is divided into different customer groups and different cost. When a TSO experience a loss of load, the TSO will get a reduction in next year income based on outage and the connected KILE cost.

The PROMAPS simulation tool calculates the power delivery reliability as a function of demand, the probability for not delivered energy for each load branch in the system and the system as a whole is calculated. Therefore the cense 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 cense cost, a system minutes (SMS) is used as an online risk indicator.

$$SMS = c \cdot \frac{E_s}{E} \tag{1}$$

Where:

E_s	:	Not delivered energy in a period T
E	:	Demanded energy in a period T
c	:	8760·60 minutes

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 indication
- 15< minutes red color indication

The color indication is shown on the single line diagram 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 decreases. If the system experience red indication the operator shall perform a power system action to reduce the level.

The simulations run every 5 minutes in the test version. Production, load, spinning reserve and grid configuration are recived from the SCADA system every 5 minutes and new simulations are performed. By plotting the power system data and the corresponding key risk result an interesting picture starts to emerge. To study how the risk indexes develop together with known power system parameter, the power system operator will get a new and deeper insight in the power system property. The figure below show: Purple curve-system production, blue curve-system load, orange curve – spinning reserve and the green curve – import/export of power from or to the system. The brown curve represent the systems SMS. By evaluating the changes in the system based on known properties and evaluate this together with the new risk curve, a validation of the risk level will emerge from the power system operators experiences.

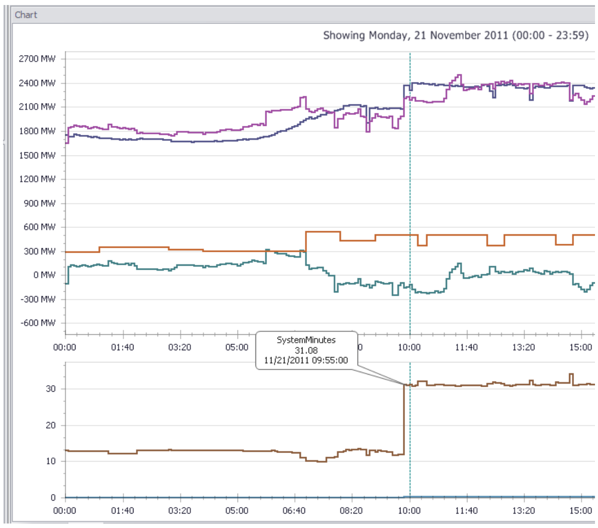

Figure 4. Risk curve (brown) and power system curves

F. *Graphical user interface GUI*

An important task in the project was to design a easy to use user interface. The user interface should be familiar for the operators already existing SCADA interfaces.

1) *Online mode*

In online mode only key risk parameters are available. The defined risk level together with the dynamic color indication will give the an operator overview after a "look" at the screen. If the risk level is higher than the set limits the operator should evaluate a power system action to reduce the current risk.

The operator can copy a snapshot from online mode to study mode.

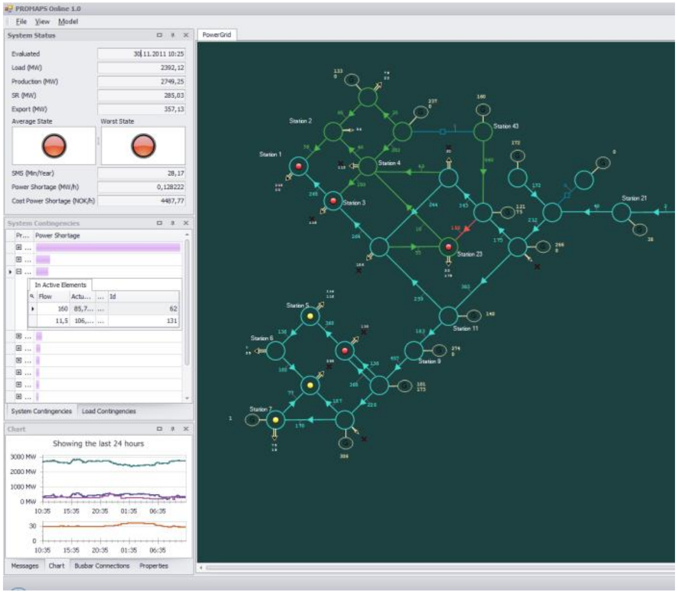

Figure 5. Promaps screen shoot

2) *Study mode*

In study mode the power system operator can test which power system action that will be the best action to reduce the risk and at which cost.

The study mode can be used for short time planning of the power system, or in semi online modus for choosing the right proactive risk action in operation situation or in long term planning of new power system investments.

IV. Calculation Principle

A typical calculation sequence in PROMAPS includes the following main functions:

1. Creation of branch reliability models based on unit Markov models and composition and aggregation of states. The operations composition and aggregation of states are described in detail later in the article.
2. Selection of a subset of states containing all grid reliability states with a significant reliability.
3. Calculation of maximum power delivery capacity for each of the significant grid reliability states based on an object function with constraints
4. Calculation of expected power shortage and creation of delivery reliability models based on the operations composition and aggregation

5. Calculation of delivery probability, mean visiting duration and visiting frequency for functioning and failed delivery states.
6. Post calculation of various auxiliary variables including economic data.

The analysis can be performed for various load profiles. For online reliability assessments, parts of the calculation sequence are repeated whenever new online data is available. Usually, new data will consist of a new online load profile, and retrigger calculation of step 3 to 6.

Important functions in this calculation sequence are further described in the following.

A. Basic reliability theory

1) Markov / Kolmogorov models

The Markov / Kolmogorov model represents a general method to describe the probability that a system is in a reliability state defined by the vector $\boldsymbol{\xi}$. The model has the following form (Endrenyi 1978).

$$\dot{\mathbf{p}} = \mathbf{A}\mathbf{p} \tag{2}$$

where **p** is the probability vector describing the probability to stay in the reliability states ξ, $\dot{\mathbf{p}}$ is the rate of change of **p** [1/year] and **A** is the transition rate matrix [1/year]. An additional requirement to the model is that $\sum \mathbf{p}=\mathbf{1}$. Dynamic solution of this differential equation requires a starting value for the probability vector **p**. However, the stationary solution is independent of the starting value.

Two important variables concerning reliability analysis in addition to the probability are the mean visiting duration and visiting frequency for the different reliability states. These variables are defined by (Endrenyi 1978):

$$\boldsymbol{\theta} = -diag\left(\mathbf{A}\right)^{-1} \tag{3}$$

$$\mathbf{v} = diag\left(\boldsymbol{\theta}\right)^{-1}\mathbf{p} \tag{4}$$

where $\boldsymbol{\theta}$ is the mean visiting duration vector [year] and **v** is the visiting frequency vector [1/year]. The mean visiting duration is the mean time spent in a reliability state at a visit and the mean visiting frequency is the mean number of visits to a reliability state each year.

2) Model composition

Assume a system consisting of two independent components with the component Markov models

$$\dot{\mathbf{p}}_\alpha = \mathbf{A}_\alpha\mathbf{p}_\alpha, \quad \dot{\mathbf{p}}_\beta = \mathbf{A}_\beta\mathbf{p}_\beta \tag{5}$$

Assume further that the system probability is given by combining the component reliability states. This probability can be expressed as $\mathbf{p}_s = \mathbf{p}_\alpha \otimes \mathbf{p}_\beta$ where $\otimes$ is the Kronecker product (Sasty 1999 p. 99). Time derivation of this expression gives further $\dot{\mathbf{p}}_s = \dot{\mathbf{p}}_\alpha \otimes \mathbf{p}_\beta + \mathbf{p}_\alpha \otimes \dot{\mathbf{p}}_\beta$. Inserting the component models in this relation and rearranging using the Kronecker relations gives finally the composite reliability model

$$\dot{\mathbf{p}}_s = \mathbf{A}_s\mathbf{p}_s \tag{6}$$

$$\mathbf{A}_s = \mathbf{A}_\alpha \otimes \mathbf{I}_\beta + \mathbf{I}_\alpha \otimes \mathbf{A}_\beta \tag{7}$$

where $\mathbf{A}_s$ is the composite transition rate matrix, $\mathbf{I}_\alpha$ and $\mathbf{I}_\beta$ are identity matrixes with dimensions corresponding to the probability vectors. Note that equation (6) is in standard Markov / Kolmogorov form. Mean visiting durations and visiting frequencies are therefore also available from the transition rate matrix $\mathbf{A}_s$ for the composite system model. This principle can be used recursively to compose large dimensional models based on simple unit models.

3) Model aggregation

High dimension probability vectors are difficult to interpret. More insight is obtained by aggregating the probability vector. Typical aggregated reliability states are {Functioning system, Failed system}. Aggregation of a probability vector can be defined by

$$\mathbf{p}_a = \mathbf{D}\mathbf{p}_s \tag{8}$$

where $\mathbf{p}_a$ is the aggregated probability vector, $\mathbf{p}_s$ is the un-aggregated system probability vector and **D** is the aggregation matrix. An additional requirement is that $\sum \mathbf{p}_a = 1$. This requirement is satisfied if the column sums of **D** are 1. Also an aggregated transition rate matrix can be calculated according to a function of the type

$$\mathbf{A}_a = \mathbf{f}_a\left(\mathbf{D}, \mathbf{A}_s, \mathbf{p}_s\right) \tag{9}$$

It is possible to show that the aggregated variables satisfy the standard Markov / Kolmogorov equation

$$\dot{\mathbf{p}}_a = \mathbf{A}_a\mathbf{p}_a \tag{10}$$

The matrix $\mathbf{A}_a$ contains therefore the necessary information to calculate the aggregated mean visiting durations and visiting frequencies.

4) Creation of branch and grid probability models

An electrical power grid is assumed to consist of branches connected by nodes. A branch may consist of generators or power import branches, transmission lines, transformers and load or power export branches. The branch reliability description may be grouped in power transmitting components, protection and reclosing components, human factors and environmental factors. Reliability diagrams are an efficient description of the component interconnections. All these groups consist of several components with reliability that can be described by Markov models and these models can be concentrated to a simple model for each branch by composition and aggregation. The models are normally reduced to the reliability states {Functioning, Failed}.

5) Selection of significant grid reliability models

If each branch has the two concentrated reliability states {Functioning, Failed}, then the number of reliability state combinations for the whole grid is 2^n where n is the number of branches. This number is growing very fast with an increasing number of branches and the number of states soon becomes unmanageable for any computer. However, only a small subset of these combinations will contribute to the grid reliability assessment. This number of significant grid reliability states is denoted Θ. For each of these states Markov grid models can be calculated and finally a global grid Markov model can be established. The reduction is partly based on a maximum number of expected simultaneous failed branches and partly on a probability limit for the reliability states. The final subset can be selected with a predefined accuracy.

6) Calculation of maximum available power delivery

Maximum power transmission in the grid for the relevant reliability states Θ is calculated by the following maximization

$$\hat{\mathbf{P}}_i = \arg\max\left(J / \mathbf{M}_i, \mathbf{B}_i\right) \quad i \in \Theta \tag{11}$$

where $\hat{\mathbf{P}}_i$ is a vector containing the maximum power transmission in the grid branches, J is a cost function that is maximized subject to the electrical grid model $\mathbf{M}_i$ and the grid operation constraints $\mathbf{B}_i$. The index i designates the actual grid reliability states. The grid models can be of various complexities from simple linear models to comprehensive nonlinear models. However, to save calculation time simple linear models is preferred. Failed branches can be modeled by restricting the power transmission normally to zero for the actual branches or by removing the branches from the configuration matrix.

7) Calculation of expected power shortage and creation of delivery reliability models

Power shortage for the various reliability states is obtained by calculating the positive difference between demanded power and maximum available power delivery.

The power delivery shortage splits the delivery models in two groups. This result can be used to generate an aggregation matrix that is used on the global grid Markov model to generate the power delivery Markov model for each delivery point in the grid. When these models are known, the delivery and delivery shortage probability together with mean state duration and visit frequency can be calculated for all delivery points.

8) Post calculations

Expected power shortage in each branch and each grid combination is calculated by multiplying the power shortage by their probability. The power shortage cost is further obtained by multiplying the expected power shortage and a defined power shortage price for each load point. Also a more involved cost factor called KILE and a power efficiency factor is calculated. In addition, a lot of other interesting variables can be calculated with the available information, as described in previous section.

V. Discussion

The ongoing Statnett R&D project has developed a methodology for calculation of online power delivery reliability for use in power system operation and planning of operation. The methodology developed has proven to be well suited for the large meshed power systems reliability calculations.

A major benefit of the method is the calculation efficiency. Current version of the computer program is able to calculate reliability indices for the Norwegian power grid within minutes. The project has also developed methodology to incorporate widespread geographical phenomenon such as bad weather into online risk assessments. This allows the operators to take actions to minimize the risk of power shortages during an emergency situation, and gathering information in the daily operation on how the risk changes.

By evaluating risk with very little delay from receiving of process values to calculated risk together with the known electrical evaluation parameters are available; a new operation philosophy can emerge and be the first step in challenging the N-1 criteria.

References

[1] Billinton, R. Allan, R.N. 1983. *Reliability Evaluation of Engine Systems, Concepts and techniques*. Plenum Press, New York

[2] Endrenyi, J. 1978. *Reliability modeling in Electric Power Systems*. Wiley, New York.

[3] Høyland, A. Rausand, M. 1994. *System Reliability Theory, Models and Statistical Methods*. John Wiley & Sons.

[4] Rausand, M. Høyland A. 2004. *System Reliability Theory; Models, Statistical Methods, and Applications*. Jon Wiley & Sons.

[5] Sasty, S. 1999. *Nonlinear Systems. Analysis, Stability, and Control*. Springer. New York.

[6] Svendsen, A. B. 2002. *Pålitelighetsanalyse for vern- og kontrollutstyr i transformatorstasjoner*. Master thesis, NTNU, Norway

[7] Wang, X. McDonald, J. R. 1993. *Modern Power System Planning*. McGraw-Hill, London