Vysus Group

Whitepaper

Representation of power system networks as a function of regularity properties

Goodtech 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. In order to analyse and understand all risk and reliability changes every 10 minutes for the large network a new representation method must be developed and tested.

In this paper a new methodology for representation of how changing risk level can be presented for power system operators is introduced. By manipulating the geographical representation of the 7000 branched power system based on calculated risk levels and power flows, it should be possible to, by "one look at the screen", understand the current risk level and weigh the changes occurred.

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 has 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 the simulation program Promaps was designed for offline analysis, it was early recognized that the concept also was suitable for online analysis. In 2009 an agreement between Goodtech Projects & Services 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.

The industry standard for visualising the power system consists of nodes being positioned relative to each other, with respect to their geographical position, with straight lines representing cables and connections. During testing and verification of the online risk simulation tool, the need for new ways to visualise large networks rapidly became obvious.

More expressive and informative overviews over the power system may be produced by lessening these established constraints regarding visual representation.
In order to analyse and understand all the risk and reliability results every 10 minutes for the large network, a new representation of the changing risk level has been developed and tested.

Similar experiments on graphs in general have been heavily researched in the recent years (Landesberger, 2011). This is partly due to graphs of larger sizes appearing in several domains and due to more powerful processing capabilities on computers.

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 introduce some of these latest graph visualisation techniques into the realm of power system network analysis. In the following sections, we will present three different techniques applied on a power grid, edge bundling, focus and context visualisation and non-geographic graph layout with clustering.

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, and how new techniques can be used to enhance visualisation. A brief description of "non electrical" applications is presented in section 5. The conclusions are presented in section 6.

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 analyse the reliability of supply, additional tools are needed.

2.1 Calculation tool

It is easy for a TSO to recognise 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.

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 Visualisation

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. However, it's not enough to receive the data, the operators must also be able to understand it, analyse it, and if necessary take precautionary actions.

This cannot be achieved in a satisfactory manner using tables and graphs, and conventional visualisation techniques do not offer the necessary flexibility. Illustrating the state of the power system using fixed nodes and straight lines limits the amount of data that can be presented to just a few key parameters. In general, all information must be presented using only changing colors and numbers. There are several drawbacks to this approach.

1. Only a very limited amount of information can be shown at any given moment
2. In order to show the entire grid, a large number of big screens must be used, making it hard to get an overview

It is however not enough to create a new visualisation technique. It's even more important to obtain and select the most relevant and useful information.

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:
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 update at every iteration.

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).

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 a few thousand contingencies, but will usually cover close to 99% of the complete probability space.

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 prioritised according to cost of not delivering energy. The methodology also supports different kinds of system protections.

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.

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.

Presentation of results

4.1 Risk parameters

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.

4.2 Standard operational view

Currently the SMS index is being used to set the limits for the dynamic colour 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 colour
- 10-15 minutes, yellow colour
- >15 minutes, red colour

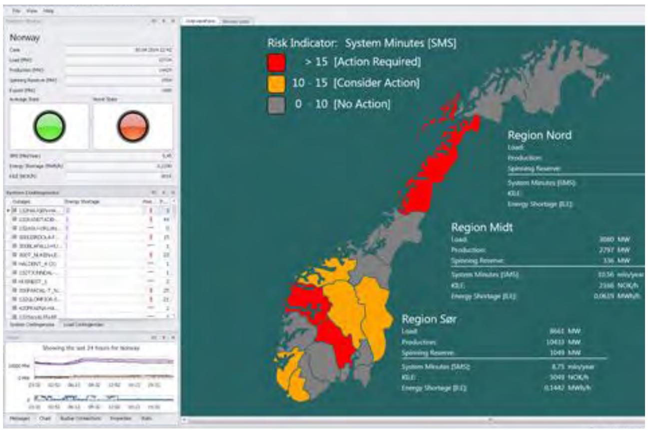

Figure 1: Overview of the risk level in each region

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

The colour 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.

The TSOs need several such images in order to cover the entire grid. In addition, if a critical component lies on the boundary between two areas, it will be hard to get an overall picture of how actions carried out by the operator will impact the system in both regions.

4.3 Edge bundling

Edge bundling is a technique where edges are attracted to each other so that edges that both move in the same direction and are next to each other bundle together into so called edge bundles. When the destination nodes are reached, the edges fan out from the bundles. The advantage of this method is most dominant in examples where the amount of edges is very high and connections are crossing each other in all directions. For such situations, normal straight edges will result in having the visual area overdrawn with edges so that none are discernible from each other. See Figure 3.

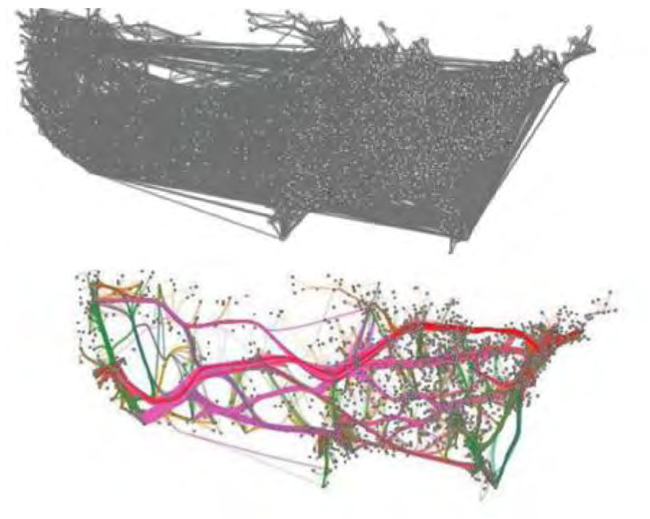

Figure 3: Edge-bundling. Naive visualisation of migra-tion between states in the US. Edge-bundling reduces clutter

Bundle thickness as well as colour representing degree of flow adds extra information (right) (Cui, 2008).

To demonstrate this technique on the Norwegian power net, we have artificially added an extra amount of edges in the central part of the country and compared the result with original straight edge visualisation (left) and edge bundling (right) in Figure 4.

The large square shows how edges are clustered into groups so it is easier to follow them. The small square shows a node with three edges going out in a similar direction and how the clustering of them before they fan out gives a more visually pleasing and easy to trace presentation. In general the visualisation becomes more organic when using edge bundling. The technique could be particularly useful for power systems which have connectivity more similar to the one in Figure 1.

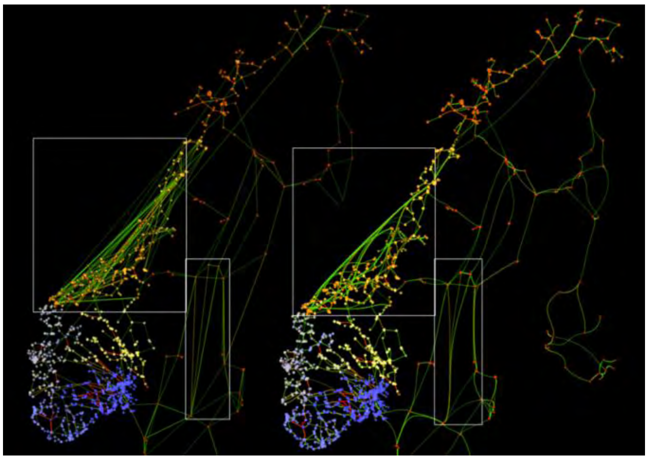

Figure 4: Demonstration of normal visualisation (left) and edge bundling (right) on the power net of Norway. Extra edges have been added in the large box for demonstration purposes.

4.4 Focus and context visualisation

Focus and context visualisation is the technique of showing in the same visualisation both details on the area of importance for a particular task (the focus area) and at the same time provide an overview so one can see the relations between the detail and the whole system (the context). The state of the art report (Herman, 2000) presents focus and context for the field of graph visualisation.

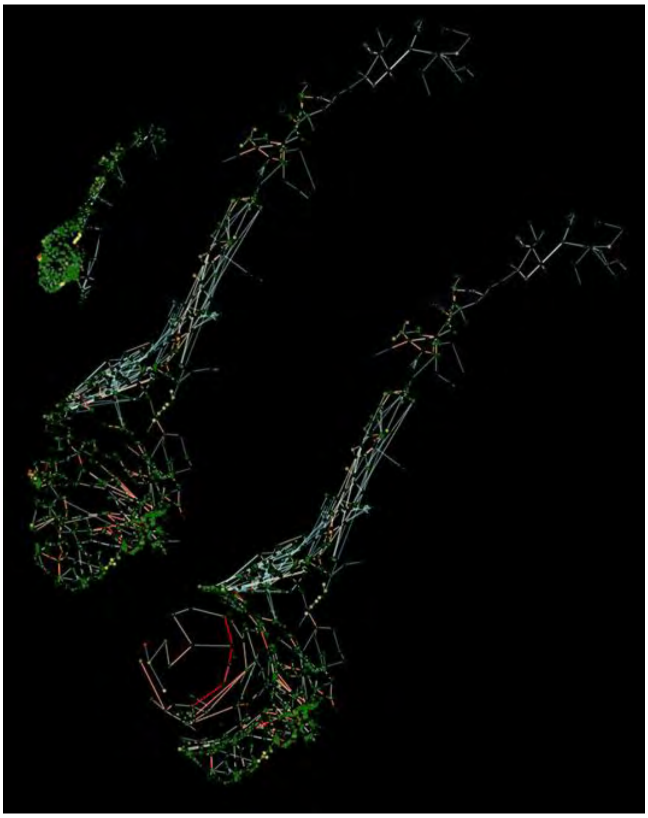

Figure 5: Three different views of the power net of Norway. SMS levels on nodes indicating capacity are colored from high to low with the colour scale green-yellow-red.

Figure 5 shows three different views of the power system in Norway. SMS levels on nodes indicating capacity are colored from high to low with the colour scale green-yellow-red. Edges are colored according to percentage of max flow with colour scale blue-yellow-red where red is maximum. The smallest map to the left gives a compact overview. One can identify two areas being yellow and one being red. The center map has a higher zoom for better details while the rightmost map exhibits the focus and context property where the area which was red has been zoomed in on while displacing the nodes and edges around. One can imagine several such zoom ins simultaneously on areas of particular importance.

Figure 5 shows such a focus and context example where the whole grid is shown as context while the area of maximum load is shown expanded in such a way that the neighboring nodes and edges are being pushed away. Such visualiszation can be made dynamic so that areas of importance get larger screen space while less important areas shrink, but still maintaining an overall correct geographic placement of the nodes.

4.5 Non-geographic Graph Layout with Clustering

In this section we will demonstrate the effect of giving the network a new layout which is not based on geographic location, but on an abstract placement that distributes nodes and edges for reducing overlap and having a more even distance between nodes by spreading nodes that are very close to each other.

One of the main challenges of visualisation of risk results is the complexity of causes and effect that comprises the results. The main contributing causes to the result might be located far from the load points affected, thus making it difficult to compress all relevant information into a single picture. For instance, a large industrial load can be greatly dependent on a few power lines supplying power to a greater topologic area. Usually the TSO are aware of these cuts, and monitor them, but new critical cuts might suddenly arise in if the total load of the system rises or maintenance work is performed on some parts of the power grid. It might thus be more appropriate to move away from the classical power grid views, and instead develop methodology for dynamic power grid view that do not focus on flow and topology, but instead highlights critical cuts and components. The idea is to make a picture of the power grid that hides away everything that is performing normal, and instead emphasizes on the few components that are critical for the reliability of the power grid. Such an approach might also lead operators to a better understanding of reliability in power grids.

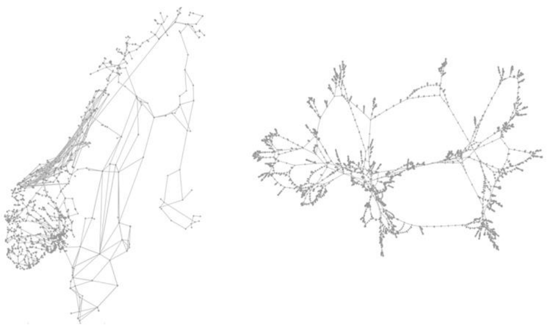

Figure 6: Figure on the left shows geographic layout while the one on the right shows abstract layout.

Figure 6 clearly illustrates how an abstract representation of the power grid can help emphasise the most important components.

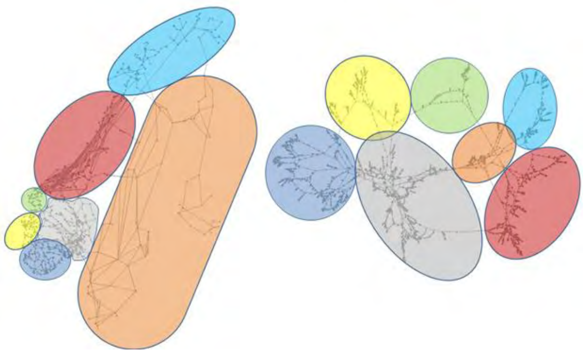

Figure 7: Figure on the left shows geographic layout while the one on the right shows abstract layout. Col-ors are added in order to easily identify the geograpic locations.

In Figure 7, colors are added to easily differentiate the different geographic regions in the abstract network.

It can be seen that the abstract representation in Figure 7 clusters the region into parts that have weak connections in between. This can be helpful for identifying vulnerable connections and meaningful clusters.

In Figure 8 connections between clusters are shown only as single edges. The number on the edges tells how many actual branches there are between the clusters. As can be seen, few edges connect the clusters with each other. The colour coding is identical to the image to the left in Figure 7.

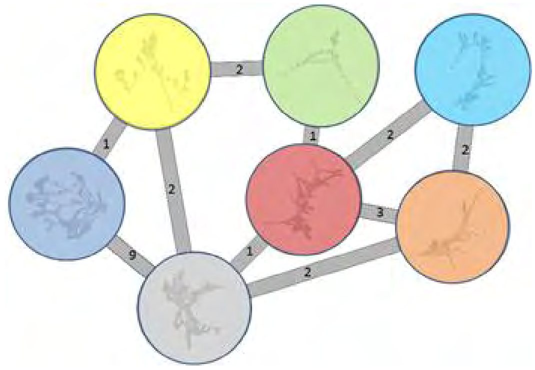

Figure 8: Regions shown as clusters, with single edges representing connections between clus-ters.

Compared to Figure 7, the subgraphs in each cluster are represented in a more untangled way, as the connections are combined in superbranches instead of single edges. All clusters can easily be viewed in more detail by zooming in, with more information being included in the picture for each branch and node.

One of the main benefits of the clustering approach is that changes in network topology, as a result of outages or maintenance can easily be spotted, as the cuts are dynamic. If critical lines are out of operation, the entire representation will change, and new critical components will immediately be prominent.

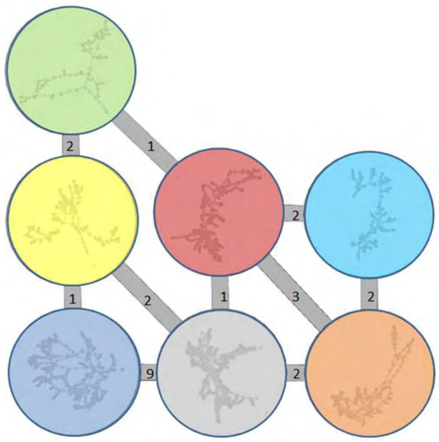

Figure 9: Regions shown as clusters, arranged in a regular grid.

Each of the clusters can be further split up into subclusters, that, when zoomed in on will show the most critical components within a given region, as shown in Figure 10.

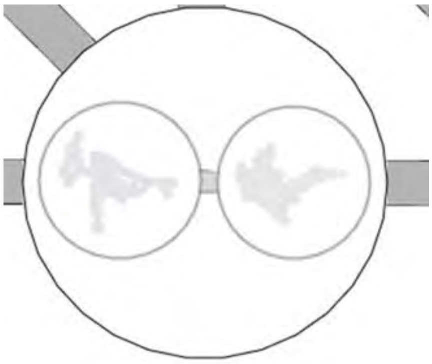

Figure 10: Splitting of clusters into subclusters

Figure 11 shows how the system state can be shown in a very simple way using the clustering technique. The values in the supernodes show the SMS values, whereas the numbers on the superbranches represent the branch flows as a percentage of the maximum capacity.

Coloring of supernodes can be used to indicate information about energy surplus/deficiency in each area or the amount of spinning reserves in each area. These are important contributors to the overall risk calculation results.

5 “Non-electrical” applications

Typical non-electrical applications are fluid flow systems including oil flow, and general material transport. Presumably also traffic and communication systems can be analysed by this method. In these cases the power flow model is replaced by the actual system model. The principle based on unit models can also be used in general probability and reliability calculations to build extremely large models.

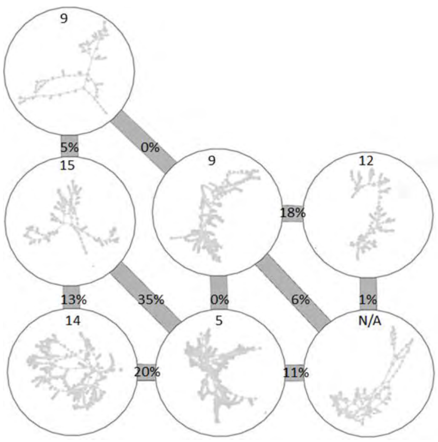

Figure 11: Values in supernodes represent SMS. Values on superedges represent percentage of maximum capacity.

6 Conclusions

After installing the new simulation tool for reliability studies at Statnett SF, the need for a customised presentation method has become prominent. Several approaches has been implemented and tested, some of which are included in this paper.

The most promising approach has been the graph layout with clustering. This approach gives the opportunity to, by a single look at the screen, identify the most critical cuts, and get an overview of the risk level in each area along with the state of the power system as a whole. By zooming in on a cluster, more information regarding the risk related to each individual branch and bus is shown.

The focus and context approach is particularly suitable if the operators want a complete overview of the power system, while still being able to identify individual critical components. It offers a great way of visualising changes in a network over time, as different parts of the system will be prominent, depending on the current risk level in each area.

7 References

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