Analysis of Misoperations of System Protection Schemes in The Nordic Grid 1st of December 2005

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Abstract

On the 1st of December 15:02 (CET) a fault on a 420 kV breaker at the Swedish Porjus power plant correctly triggered the breaker failure protection, and the 420 kV busbar at Porjus power plant was disconnected. This led to that the remaining power transfer corridor out of northern Scandinavia got overloaded. The overloading should have led to instantaneous triggering of a system protection scheme to limit the damage. However the system protection scheme did not work as intended.

The malfunction of the system protection scheme led to two major islands in the Norwegian grid, and 2450MW of generation disconnected from the Nordic grid. The Nordic transmission system has a design maximum production loss of 1200 MW. The operation of the grid outside design limits led to unwanted triggering of a second system protection scheme, which should have led to shedding of another 1000 MW of production from the Nordic grid. Fortunately malfunctioned this system protection scheme also.

This paper discusses the results of the investigation of this event, addressing the following items:

1. Analysis of the event from pendeling (10-20 Hz) recordings of power and frequency;
2. Causes for misoperations that occurred during the event;
3. Restorative actions by dispatchers;
4. Impact of the event on design and implementation of system protection schemes in the Nordic grid.

Introduction

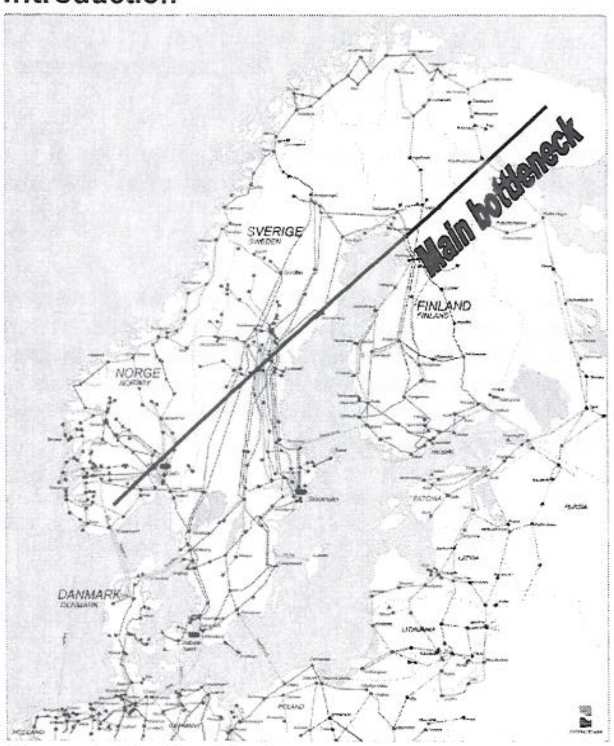


Figure 1: The Nordel grid

The electrical grid in Norway is a part of the Nordel electrical system, which encompasses the electrical grids of Norway, Sweden Finland and Eastern Denmark. The Nordel grid and market is in balance with regard to energy and has an installed capacity of 89000 MW and a maximum load of 69000 MW. The production is 53% hydroelectric and the rest is thermal/nuclear.

The main bottleneck in the Nordel grid is also shown in Figure 1. This bottleneck is between most of the hydroelectric power plants (northwest) and the thermal and nuclear production (southeast). The main consumption is also southeast of the main bottleneck.

In Norway two system protection schemes have been implemented to deal with problems with high production northwest of the main bottleneck. These system protection schemes are implemented in the following manner: An area is connected to the rest of the power system through a predefined bottleneck. If transfer on the bottleneck exceeds a predefined limit, the power system dispatcher sensitizes the system protection scheme. If the bottleneck is restricted due to a disturbance (i.e. a set of predefined breaker operations), production within the area will be automatically tripped by the system protection scheme. The system protection scheme may also introduce a net split. In the further the two system protection schemes are described in some detail.

System protection scheme "Nordland"

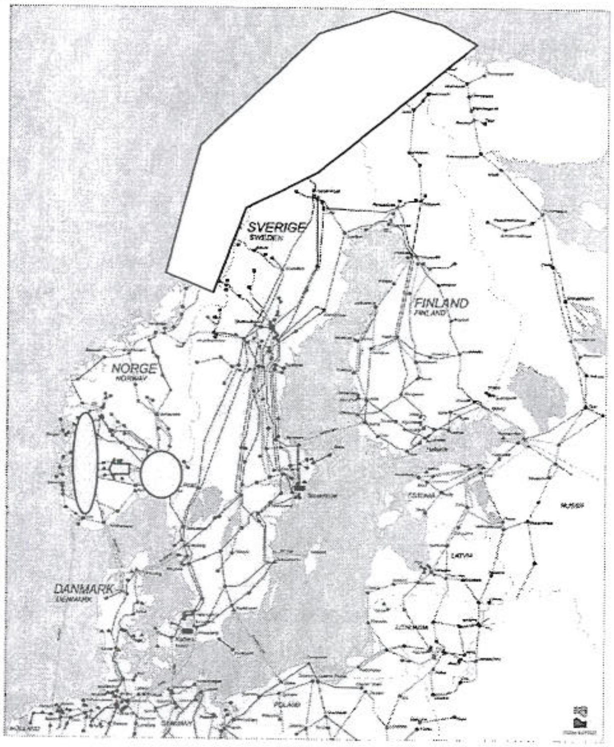


Figure 2: System protection schemes "Nordland" and "Østland"

The white-shaded area (northern Scandinavia) in Figure 2 contains nearly 15% of the installed hydroelectric capacity (~6000 MW) in the Nordel grid. At the same time the consumption is relatively low.

If one of the power transfer corridors (PTC's) out of the white-shaded area (420 kV through Northern Sweden or 300 kV through Middle Norway) is disconnected, or if there is a grid split inside the area, the power flow on the remaining PTC must be restricted to keep the PTC in service. An important point is that if all production within the area is disconnected from the grid, this will be higher than the dimensioning production loss (1200 MW) for the Nordel grid.

If system protection scheme "Nordland" is sensitized it will work in the following manner:

- Trip production. Up to 900 MW of production may be tripped.
- The system protection scheme may also disconnect the northernmost part of Norway from the main Nordel grid. In this manner even more production is disconnected from the system. This part of the system protection scheme will only be activated when there is a production surplus in the northernmost part of Norway.

If the northernmost part of Norway is islanded by the system protection scheme, the Regional Control Centre Northern Norway has the task to get this electrical island in balance with regard to production and consumption before this part is reconnected to the Nordel grid.

System protection scheme "Østland"

The main load centre in Norway is in the eastern part around Oslo, with nearly half of Norway's population (circle in Figure 2). There might be a problem with power transfer capacity either to the Oslo area, or from Norway to Sweden in cases where there is a high transfer from west to east over the main Nordel bottleneck. In these cases system protection scheme "Østland" will be sensitized. This protection scheme will in cases of outages or overload on central lines in the Oslo area trip production (up to 1200MW) on the west coast of Norway (ellipsis in Figure 2). This production tripping will lighten the load on the remaining lines in the Oslo area.

Sequence of Events 15:02 1st of December 2005

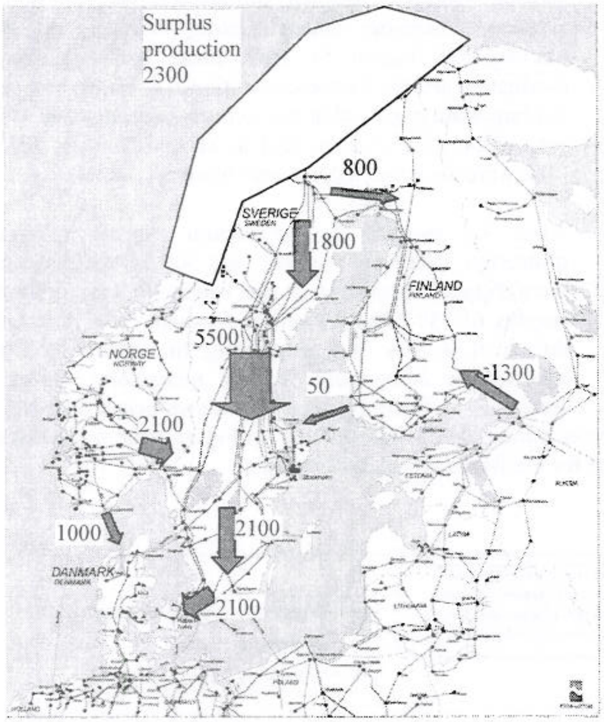


Figure 3: Main power flows 1st December 2005 before the incident

The situation 1st of December in the Nordel grid was characterized by high hydroelectric production northwest of the main Nordel bottleneck (see Figure 3). System protection scheme "Nordland" was sensitized due to high production in northern Scandinavia (2300 MW out of the area). Both the net split and production tripping were sentizied.

In addition the system protection scheme "Østland" was sentizied because of high transfer from Norway to Sweden (2100 MW).

The situation was in no way unusually strained for this time of the year. Regional Control Centre Northern Norway had allowed relay testing on a line differential protection on 420 kV, and Regional Control Centre Southern Norway had a major upgrade on the SCADA system, which caused a considerable delay on both measurements and indications.

In Northern Sweden (Porjus power station) a 420 kV reactor was to be disconnected. On 15:02:33 the breaker command was issued but one phase failed.

The 420 kV busbar differential protection in Porjus did clear the fault, thereby shutting off one of the main PTC's from Northern Scandinavia through Sweden. This should have led to instantaneous shedding of 900 MW of production, and an islanding of Northern Norway thereby shedding a total of 1030 MW of production from the Nordel grid. This did not happen.

On the Swedish side the system protection did work as intended, and tripped 600 MW of production. The remaining 1700 MW of surplus production was pressed southwards through the grid in Norway. This led to overload on the remaining lines, and a 220 kV line between Sweden and Norway tripped after 800 ms and two 300 kV lines between North and Middle Norway tripped after 850 ms (cf. Figure 4).

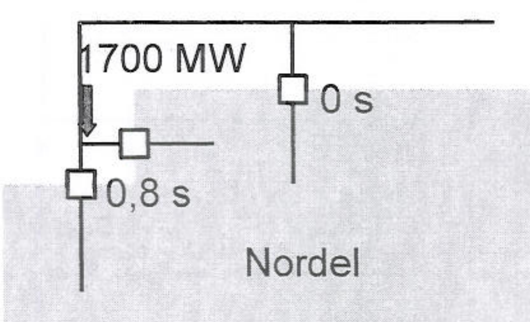


Figure 4: Schematic on fault development 0s to 0,8 s

The total production loss from the main Nordel system was now 2450 MW, as some hydroelectric production in Sweden tripped due to the initial fault in Porjus. In addition 150 MW of load tripped due to the voltage dip when the grid was divided.

The production surplus in the islanded area led to a rapid frequency rise within the area, and the loss of production from the main Nordel grid led to the greatest recorded frequency deviation for the main Nordel system (0.8 Hz).

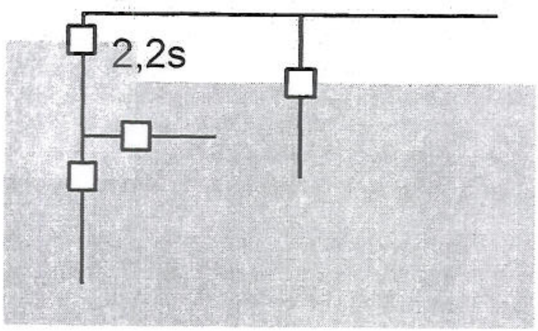


Figure 5: Situation after 2,2 s

After 2,2 s the grid split function of the system protection scheme "Nordland" reacted, and the area was split into two sub-areas, hereafter called Middle Norway and North Norway (cf. Figure 5). Both areas had a surplus of production and the frequency continued to rise in both areas. An important point is that due to over-frequency 300 MW of production were disconnected in Middle Norway, and 187 MW were disconnected in North Norway.

After 3.3 seconds the production tripping of system protection "Nordland" reacted, and 300 MW of production were tripped. North Norway that originally had a production surplus of 430 MW at nominal frequency did now have a deficit of 40 MW (not considering the reduced production due to the droop curve of the generators). Hence the frequency in North Norway went down below 48,5 Hz, and automatic under-frequency load shedding at 48,5 Hz disconnected 128 MW of load. In Figure 6 the frequencies for the Nordel area, Middle and North Norway are shown for the first 25 seconds of the fault.

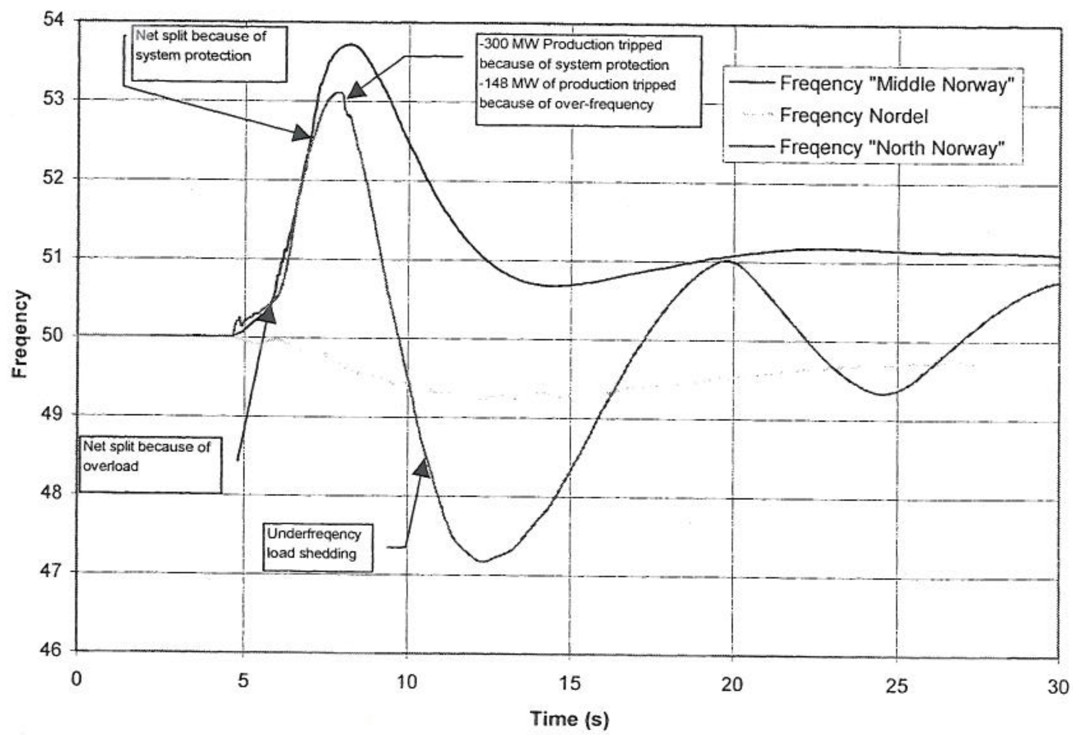


Figure 6: Frequency first 25 seconds of fault

The frequency drop in the main Nordel grid as Middle and North Norway was disconnected caused activation of spinning (frequency) reserve in Nordel. This automatic production rise in the remaining system was divided between the Nordel countries as such: Sweden 600 MW, Finland 450 MW, HVDC tie-lines to other grids 480 MW (Russia, Central Europe), and Norway 1050 MW (see Figure 7). Nearly all of the increased production in Norway was on west coast.

Figure 7: Change in production and power flows in Nordel grid due to loss of 2450 MW

The production rise led to an increased power flow of ~1200MW from west to east in Southern Norway. 400 MW of these MW's went to cover internal Norwegian power deficit, and the rest (700 MW) did go over the main Nordel bottleneck to cover up the Swedish power deficit.

The extra 700 MW on the PTC between Southern Norway and Sweden led to that the system protection scheme "Østland" triggered due to overload on one of the lines in the corridor. This system protection should have led to trip of 1150 MW production on the west coast of Norway. The system protection scheme did not work as intended, and no generators were tripped.

In the main Nordel grid the situation led to further manual activation of 2000MW of production (fast reserve) to get the situation under control.

After 15 minutes Middle Norway was synchronized in to the main Nordel grid and after 24 minutes North Norway was synchronized in the main Nordel grid. A problem in the rebuilding of the grid was that both producers and consumers were unaware of what caused the shedding of load or production. Hence both load and production was put in service without concession from the Regional Control Centers.

In total the disturbance led to a loss of load of 250 MW (70 MWh). In addition were the system protection schemes deemed unfit until the reasons for misoperations was corrected. This had consequences for the capacities on the PTC's which again led to costs of ~0,5 mill Euro. In the further the reasons for misoperations are discussed.

Findings after disturbance

Too slow reaction time on system protection "Nordland"

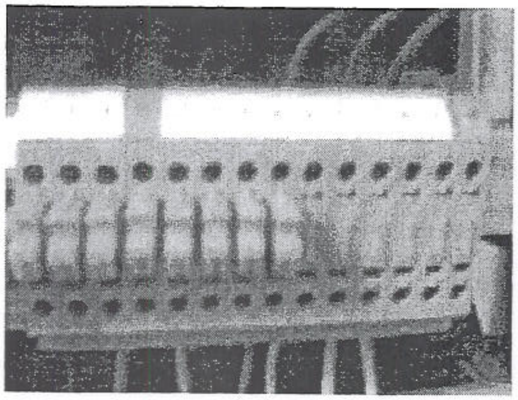
This system protection scheme was designed in 2001 and put into service. In one of the hydroelectric power stations where the response should have been shedding of 300 MW of production / a grid split, the system protection scheme was realized through software in the bay nodes. When the system protection scheme was tested in 2001 the total time was found adequate. However between 2001 and 2005 the power station owner had changed their SCADA system, and communication software for the SCADA system had been added to the bay nodes, thereby slowing down the cycle times of the nodes considerably. This was the reason for the delayed action of the system protection scheme.

More stations were found where the system protection was realized through software in bay nodes and/or station computers, and this design principle was deemed unusable, as total time could not be guaranteed. In the future system protection in the Nordel grid shall be realized through discrete components, which guarantees the total time even if the configuration of the rest of the station control equipment changes.

In short, a system protection scheme should have as high reliability as the component protection. As a consequence of this, the relay department is now made responsible for the implementation and commissioning of the system protection schemes, and new demands with respect to communication and implementation are enforced. System planning is still responsible for system protection scheme algorithm, setting and sensitizing.

Misoperation of system protection "Østland"

The triggering of the system protection scheme was as intended. However, it can be discussed if an overload situation should have led to triggering of the system protection scheme. In the current case the power system was outside design limits, as the system design production loss is 1200 MW, and the production loss was 2450 MW. This led to that more frequency/spinning reserve than designed for was brought into action on the west coast of Norway. In this way the power system was saved from heavy under-frequency load shedding or breakdown. After the disturbance the overload limit of the system protection scheme was set to a higher value, so high that it in the current case it not would have triggered.



The reason that the triggering did not lead to production tripping can be found in Figure 8. The clamps on the photography were forgotten open after a test of the system protection scheme. As a consequence new procedures for testing of system protection schemes were implemented in Statnett.

System planning decides when to test, and what shall be tested. Before a test a detailed test plan shall be issued to and approved by the system planning depatment.

In this way Statnett hopes to avoid similar situations as the one in Figure 8.

Figure 8: Forgotten to close...

Other findings

The disconnection of hydroelectric generators due to over-frequency in North Norway was unnecessary for machine protection, and led to under-frequency load shedding. Statnett has now specified for producers that over-frequency production shedding is unwanted, and shall only be used where it is necessary for machine protection.

Under-frequency load shedding was also in action during this disturbance. There were more cases of utilities connecting shedded load without the concession of the Regional Control Centre. In worst case this may lead to a blackout. Statnett has repeated the rules for bringing shedded load back into service for the utilities. A recent hurricane (with production shortage) has shown that the utilities are aware of the rules now.

Conclusion

In the case described here we were lucky to not see a total blackout of the Nordel grid. This disturbance highlights issues that have to be addressed when having system protection schemes in an electrical grid:

1. Design of system protection schemes. In the current case, the misoperation of one system protection scheme led to unwanted operation of the other. This cascading is highly unwanted. To design for contingencies is hard, and a careful design review is necessary and is now enforced.
2. Implementation and commissioning of system protection schemes. The correct operation of schemes is just as vital as correct operation of protection for the electrical grid. In Norway Statnett's relay department is now made responsible for that standard solutions are used (in case there are no standards, new ones are made), and the relay department is also responsible for that the implemented solution has as high reliability as protection.
3. Testing. New procedures for testing are made and enforced.
4. "Distributed" system protection schemes. Both the tripping of load and generation for system purposes (under/over-frequency/voltage) happens fairly seldom, and the local utilities must be aware that one must have concession from the system operator when bringing load and generation on-line. In addition good routines and tools must exist for notifying local utilities that something "big" has happened, and as to when production and load can be brought on-line. Statnett is addressing both issues.

Both Statnett and Nordel governing bodies are addressing the issues above.

Biography

Jan Åge Walseth was born in 1963 in Alta, Norway. He received the M.Sc. degree in Electrical Engineering in 1988 and the Dr. Ing. Degree in Engineering Cybernetics in 1993, both at the Norwegian Institute of Technology. 1993-1995 Dr. Walseth worked at Aker Engineering/Oslo developing tools for dynamic modeling. 1995-1997 Walseth worked at Fantoft Prosess/Oslo with design of operator decision support systems/control systems. Since 1997 he has been working at Statnett Regional Operations Northern Norway. His main tasks have been fault analysis on-site engineering, procurement and commissioning of new control equipment, and control center support. Dr. Walseth current position within Statnett is Deputy Chief of Department for Substations Operation in North and Middle Norway.

Jan Eskedal was born in 1962 in Kristiansand, Norway. He received his M.Sc. degree in Electrical Engineering in 1987 at the Norwegian Institute of Technology in Trondheim. He has been working at Statnett with fault analysis and relay planning (1988-1991) and at the National Control Centre (1991-1997). Since 1997 he has been Department Manager for the Department of relay planning and fault analysis.

Øyvind Breidablik was born in Stryn, Norway on October 9, 1958. He graduated as a Master of Science in Electrical Engineering from The University of Trondheim, The Norwegian Institute of Technology in 1983. His employment experience includes The Norwegian Power Board (Samkjøringen) and presently Statnett, the Norwegian TSO-company. His fields of interest comprise power system analyses, emergency control actions, power system operation and power system reliability and protection. Presently he is in charge of operations planning and coordination of maintenance in Statnett Grid Operations. The main issue in this position is to obtain the best utilization of existing system based on social costs. He is the Statnett member of a Nordel Working Group dealing with similar tasks.