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Operational Security Assessment - Planning and Control

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RESULT (summary)

This report summarises the main results and recommendations from the R&D project ***Operational Security Assessment – Planning and Control***. The project has been a part of the **"EFFEKT" research program** initiated by the Norwegian Research Council. The main work has been carried out at SINTEF Energy Research in the period 1996-2000. The Norwegian Transmission System Operator, Statnett SF, has been project responsible.

The project has been divided into the following sub projects:

1. Peak load capacity in view of exchange contracts
2. Reliability and security standards
3. Network analysis in combined AC/DC-systems
4. Harmonics and disturbances from HVDC and FACTS components
5. Active reserves, frequency and load following control
6. Voltage stability assessments, tools and models
7. On line applications

3 PhD students have been financed by the project. The PhD-topics have been selected within the frame of subproject 2, 4 and 7.

The documentation from the project includes 19 technical reports and 11 national and international articles and papers.

KEYWORDS

SELECTED BY AUTHOR(S)	System Operator	Power system analyses
	On line applications	Harmonic interaction

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1 INTRODUCTION

In this report main results and recommendations from the project ***Operational Security Assessment – Planning and Control*** is presented. The project has been a part of the **"EFFEKT[1]" research program** initiated by the Norwegian Research Council in 1995.

2 PROJECT DESCRIPTION

2.1 BACKGROUND

In 1995 three new HVDC[2] links between Southern Norway and the European Continent were planned: The NorNed link to the Netherlands (2001) and the Viking and the Euro links to Germany (2002 and 2003). These new links with a capacity of 600 MW each, would have increased the exchange capacity from +/-1000 MW in the existing Skagerrak link to a total of +/- 2800 MW.

The exchange contracts attached to the new links were based on a "pump storage" pattern where the flexible Norwegian hydro system was expected to support the Continent with peak power during the day and with an energy return at night-time to achieve an energy neutral exchange.

These contracts would have changed the production pattern in the Norwegian system considerably. The change from import at night to export during the day was expected to increase the need for power regulation in the Norwegian system in the morning hours from about 4000 MW to 10 000 MW. This new production pattern and the changes in power flow in Southern Norway were at the start of this project regarded as the main challenges to system operation.

Mainly due to the deregulation process in Central Europe, fundamental assumptions made at the endorsement of the exchange contracts have been changed. Lower energy prices in Germany and Holland have threatened the profitability of the projects. This has lead to a full stop in the Euro cable, project and the NorNed and the Viking projects are delayed. These two remaining projects are expected to be finalised in 2003 and 2004 respectively.

Even if the basis of this R&D project is changed during the project period, the results presented in this report are regarded as most relevant. Still 2 of 3 projects tends to be realised, which means that a total of 2200 MW exchange capacity via HVDC links will be available from Southern Norway. New load flow patterns due to extended power exchange with the Continent, a general growth in consumption and low rate of investments in grid and production capacity will surely represent challenges to safe system operation.

[1] EFFEKT is Power [MW] in Norwegian
[2] HVDC= High Voltage Direct Current

The main challenges could be categorised as technical and operational as illustrated in Figure 1.1 and Figure 1.2.

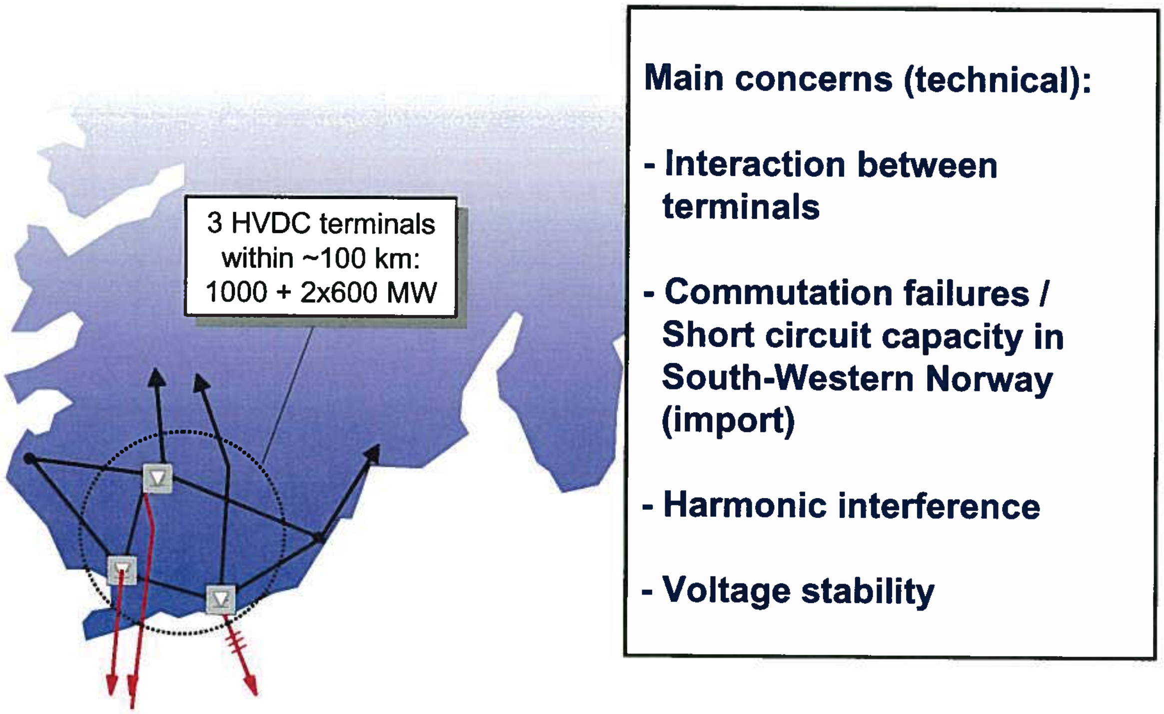

Figure 1.1 Technical challenges

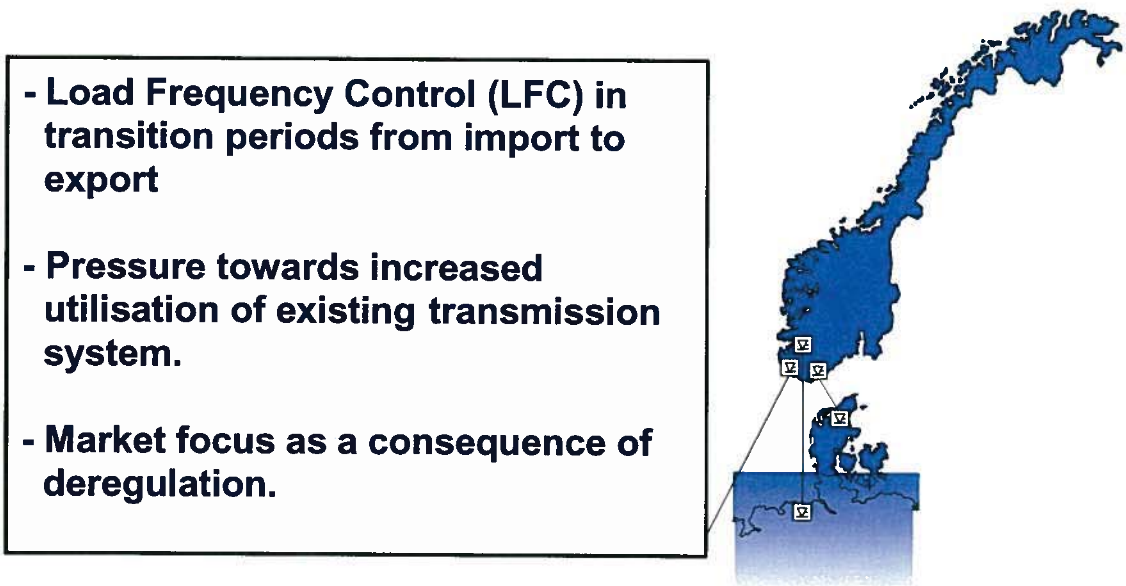

Figure 1.2 System Operation challenges

2.2 OBJECTIVE AND ORGANISATION

Main objective:
To develop methods, models and framework for operational security assessment in the Norwegian Power System in view of expected changes in operational and technical conditions due to increased power exchange through HVDC links.

Project period: 1996 – 2000

Participants: Statnett SF [3](project responsible), Norwegian Research Council, NVE[4], Enfo[5] and major power producers.

Research Group: SINTEF Energy Research (project management), NTNU and experts from Statnett.

Total cost: 19, 5 MNOK

Results: The results from the project have been presented in yearly seminars. The documentation includes 19 technical reports and 11 national and international articles and papers.

2.3 SUB PROJECTS

The project has been divided into the following sub projects:

1. ***Peak load capacity in view of exchange contracts***
2. ***Reliability and security standards***
3. ***Network analysis in combined AC/DC-systems***
4. ***Harmonics and disturbances from HVDC and FACTS components***
5. ***Active reserves, frequency and load following control***
6. ***Voltage stability assessments, tools and models***
7. ***On line applications***

In addition 3 PhD students have been financed by the project. The PhD-topics have been selected within the frame of subproject 2, 4 and 7. During the project period the research group has supported the students, and their work has been presented in the project seminars.

The progression of the project is illustrated in Figure 2.1

[3] Statnett SF is the Norwegian Transmission System Operator (TSO)
[4] NVE= The Norwegian Water Resources and Energy Directorate
[5] Enfo = The Norwegian Electricity Association

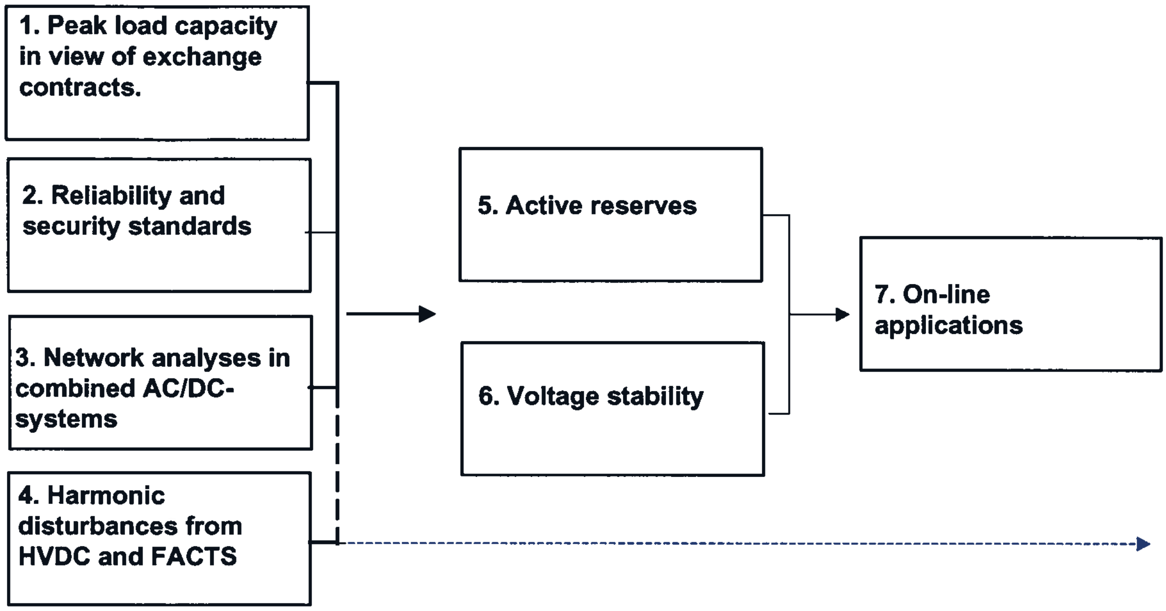

Figure 2.1 Sub projects

Sub project 4 has been dedicated to technical challenges in the terminal area of the HVDC links, and has during the project period been following its own path within the main project.

The rest of the subprojects, dealing with operational challenges, are linked together. Sub projects 1-3 are regarded as fundamental projects with respect to assumptions, preconditions, reliability and security standards, tools and analytical methods. In the second phase of the project the main aspects connected to system security, active reserves/frequency control and reactive reserves/voltage stability and control, were focused. And finally, recommended models and products from the basic projects have been further developed in sub project 7, which includes prototypes for on-line applications.

3 MAIN RESULTS

3.1 PEAK LOAD CAPACITY IN VIEW OF EXCHANGE CONTRACTS

3.1.1 Objective

To identify and define System Operator Challenges caused by extended transmission capacity to the European Continent via HVDC links.

The intention of this introductory project was to provide necessary background information regarding the Norwegian production potential and power [MW] balance, and to describe the operational consequences of the exchange contracts.

3.1.2 Results and recommendations

Documentation:

1 technical report in Norwegian [1].

HVDC-links between the Nordic countries and the European Continent

Figure 3.1 shows an updated map of existing and planned HVDC projects between Nordic countries and the European Continent. The following links are in operation: The Skagerrak connection between Norway and Denmark (1050 MW), the Kontiskan links, 1 and 2, between Sweden and Denmark (670 MW), the Baltic cable from Sweden to Germany (600 MW), The Kontek link between Denmark and Germany (600 MW) and the Sweden-Poland (SwePol, 600 MW) link (in operation this year). These links are expected to be followed by the link between Norway and the Netherlands (NorNed) in 2005 (?) and the Viking cable from Norway to Germany in 2006 (?). The capacity on these new links is decided to be 600 MW each. (800 MW has been an option.) Within 5-10 years about 4100 MW HVDC capacity will link the Nordic countries to the European continent.

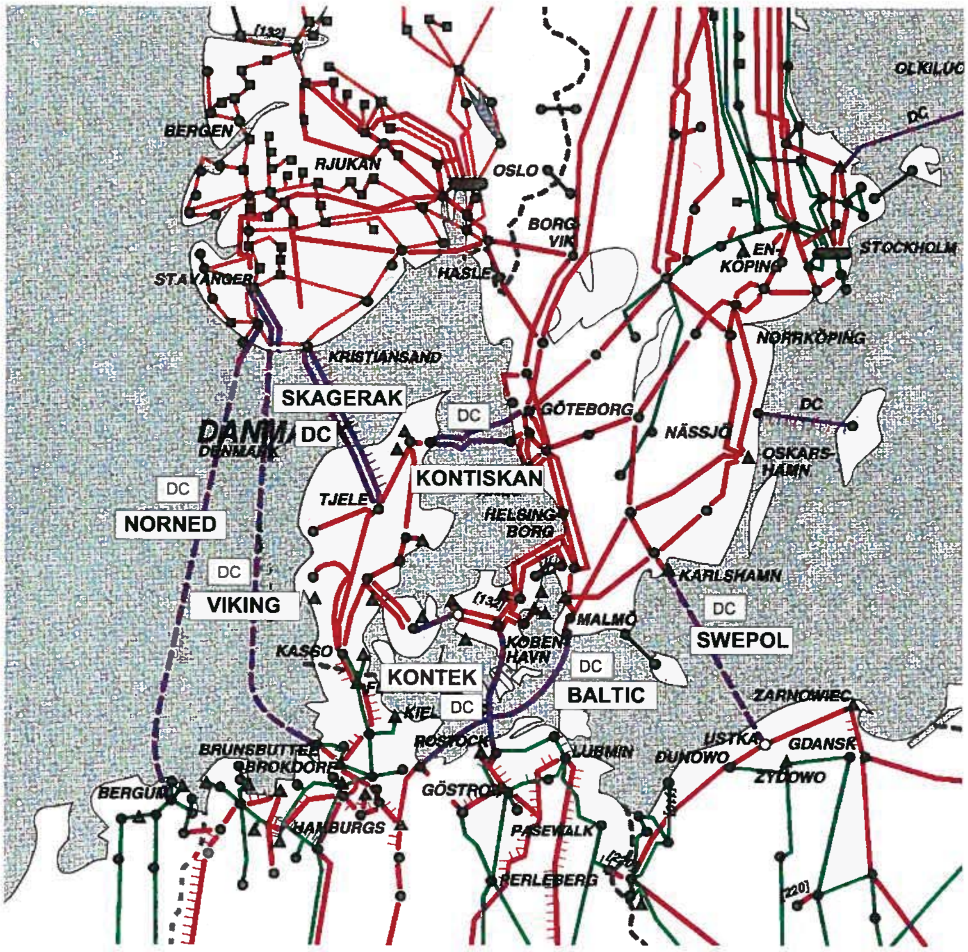

Figure 3.1 HVDC-links

Exchange Contracts

As mentioned in the introduction, the Euro-cable contract is cancelled due to reduced economic profitability. The remaining Skagerrak (existing link), NorNed and Viking contracts represent a resulting net export obligation of about 5.6 TWh. However, these contracts are more and more looked upon as financial contracts, which means that the physical exchange is dependent of the current spot price in Norway and Germany/Holland respectively. Nevertheless, import at night and export in daytime is still regarded as the basic pattern of exchange.

Scheduling and power [MW] regulation

The final production schedule in the Norwegian power system is not known before the settlement in the Elspot market. The main part of the System Operator planning with respect to security and availability must therefore be carried out in the ***pre-operational phase*** as defined in Figure 3.2. The duration of this phase, which together with the ***operational phase*** is called the ***control phases***, is from 10 to 34 hours (1400 – 0000/2400). The ***market phases*** starts with the ***price hedging phase*** (2-5 years) and ends with the ***spot phase*** which appears every day between 0700 and 1400.

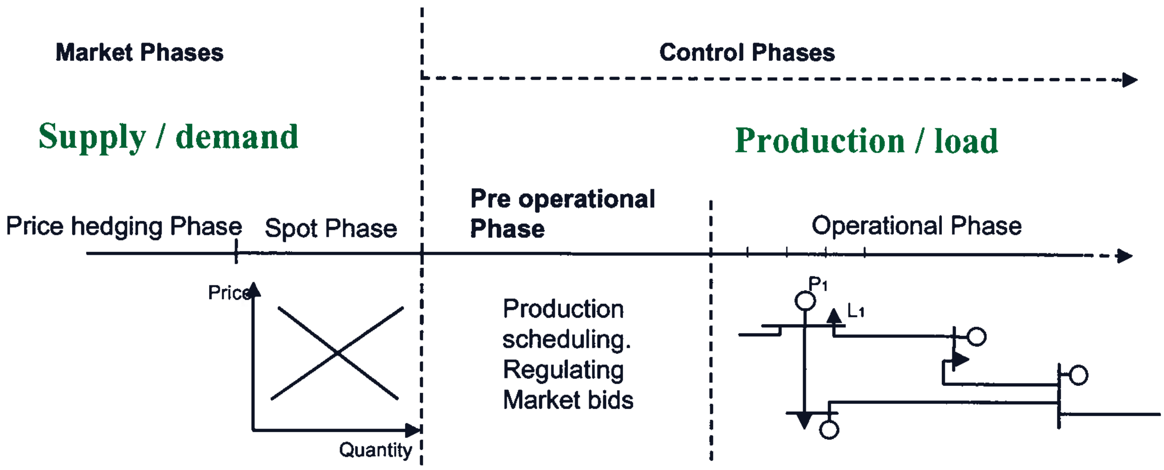

Figure 3.2 Transition from market settlement to physical operation.

The following definitions are used with respect to power control:

- ***Day to day regulation***: Scheduled generation (regulation on the hour)
- ***Primary control***: Automatic frequency control (response: 2 –5 sec.)
- ***Secondary control***: Manual production control to adjust interchanges stationary frequency and time deviations (response: 15 min.)

The contribution to primary control is in Norway an ancillary service with annual compensation, while the regulation objects for secondary control are chosen from the Regulating Power Market list for up or down regulation. The bidding in this market takes place in the pre-operational phase.

Increased pressure in the control phases to the personnel in the main control centres is expected, which means that more efficient tools for decision aid are needed.

Peak hour power balance.

The Norwegian production potential is presently approx. 27 800 MW and investments in new generation of some scale in the nearest future are not expected. An investigation carried out by Statnett in 1996, showed availability in the peak hours of only 80 – 84 % of this potential. Annual growth of 1,2 % in peak hour load is expected. This means that the load might exceed 25 000 MW in 2005. Figure 3.3 shows that import in peak hours will be necessary in about 200 hours provided load distribution as previous years.

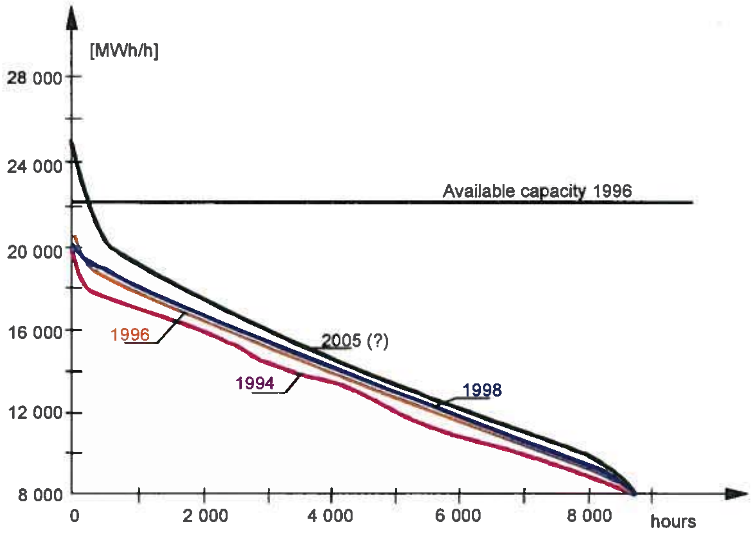

Figure 3.3 Domestic load, hourly distribution, and peak power production potential.

This means that peak hour export to the Continent will be limited in cold winter days.

Import capacity

The energy balance (MWh) shows that Norway will become a net importing nation in normal years of inflow to the reservoirs. In a dry year it is expected that all HVDC capacity will be utilised for import.

The following technical obstacles might cause reduced import capacity:

- ***Congested transmission lines in the terminal area***
- ***Short circuit capacity in the terminal area***
- ***Low domestic load compared to minimum production due to uncontrolled inflow***

HVDC-links in dynamic control

Existing HVDC-terminals have emergency schemes in order to support both active and reactive power. The exchange contracts for the new HVDC-connection opens for additional regulation schemes related to primary and secondary control. While regulation referred to voltage deviations only affect the terminal area; regulation referred to frequency deviation will affect the total Nordic synchronous area.

Primary and secondary control via HVDC-links is on that account dependent of mutual agreements based on mutual analyses (static and dynamic) on both sides of the link.

3.2 RELIABILITY AND SECURITY STANDARDS

3.2.1 Objective

- ***To develop and test a flexible criterion for determination of power transfer limits based on probabilistic models and minimisation of congestion costs and expected interruption costs.***
- ***To specify how such a criterion can be adapted and implemented as part of an on-line security assessment tool.***

This project is motivated by the new challenges for the System Operator compromising between system security and congestion costs. The competitive environment has led to increasing focus on efficient and flexible utilisation of the main transmission grid. As a result the question has been raised whether the security standards applied by transmission grid operators are too conservative.

The deterministic (N-1) criterion implies that transmission line capability is not always fully utilised. As a consequence unnecessary high congestion costs may be imposed on power producers and grid operators. Hence, one is looking for a more flexible criterion, which takes into account probabilistic failure models, expected power interruption costs and constraint (congestion) costs.

The overall aim is to enable determination of flexible power transfer limits that minimises the total costs related to transmission constraints. This involves problems and challenges related to power system security analysis, congestion management and risk assessment.

3.2.2 Results and recommendations

Documentation:

- 2 technical reports in Norwegian [2, 3]
- 3 conference papers [4 – 6]

Interface flow limits

Most transmission operators apply the deterministic (N-1) criterion for operational security assessment. A main task in daily operation planning is the determination of *interface flow limits*. An *interface* is defined as a set (or a subset) of circuits separating two portions of the power system. Thus, the *interface flow* represents the net power flow from a sending end area to a receiving end area. The determination of interface flow limits using the (N-1) criterion is an established part of the operating procedures at the National Control Centre.

The (N-1) criterion has shown to provide sufficient security. It does not, however, include any economical aspects, and it does not necessarily lead to the most cost-effective operation. It is inflexible and, for example, not sensitive to varying outage probabilities for circuits exposed to changing weather conditions.

Probabilistic Security Criterion

Preventive as well as corrective control actions in order to maintain interface flow limits imply congestion costs [3, 4]. These costs increase as the power transfer demand exceeds the transfer limits. On the other hand, if a higher transfer flow were accepted in order to reduce the congestion costs, this would reduce the security level and increase the risk of interruptions and blackouts associated with a system failure. Thus, the expected interruption costs will increase as the power transfer level increases.

This is the main idea of the probabilistic operational security criterion: To enforce flexible interface flow limits in a way that minimises the sum of congestion costs and expected interruption costs. Thus, the interface flow limits will vary with time, as a function of weather conditions, power prices and other factors affecting the grid operating costs.

The cost functions shown in Figure 3.4 illustrate how the interface flow limit is determined from minimisation of total grid operating costs.

The *congestion cost* is primarily a function of the interface flow *(F)* and the market situation *(m)*. Presented as a function of interface flow, this will typically be a decreasing function, reaching zero cost at the interface flow level which satisfies the initial market demand.

The *expected interruption costs* are the total expected customers' cost of energy not supplied resulting from a transmission grid failure. The computation involves contingency analysis combined with statistical information about failure rates and interruption scenarios determining the amount of energy not supplied. The expected interruption cost is primarily a function of the interface flow (*F*), the weather conditions (*w*), since the failure rates are known to be highly weather dependent, and the customers affected by the interruption.

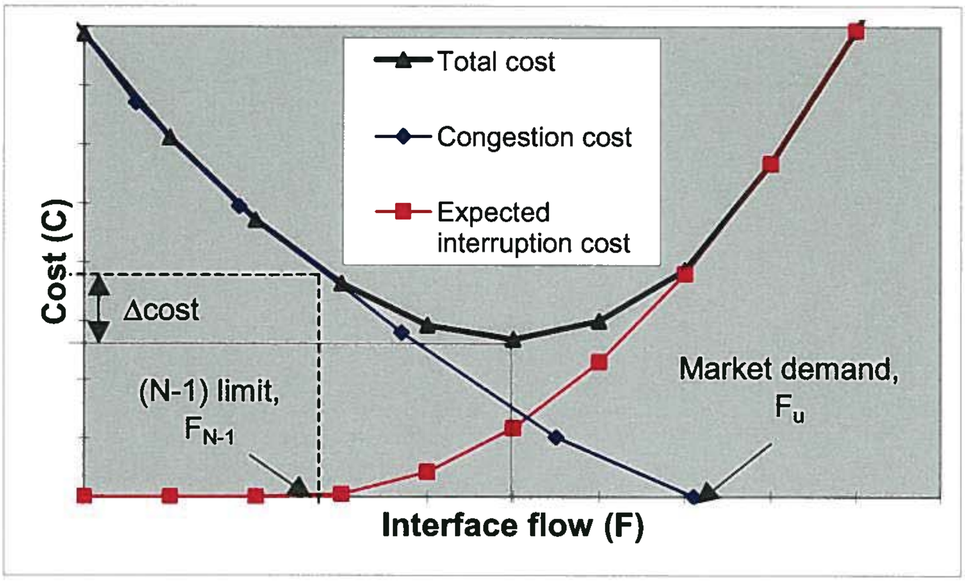

Figure 3.4 Interface flow limit determined from minimisation of total grid operating costs.

Socio-economic congestion costs

The socio-economic *congestion cost* is defined as "the cost of not having enough transmission capacity as required by the market". As shown in Fig. 3.4 the cost can be computed as a function of the applied interface flow limit.

In the Nord Pool market major transmission congestions are handled by defining separate bid areas for the physical (Elspot) market. The System Operators in Nordel specify power capacity limits between the bid areas for each hour of the day prior to clearing of the Elspot market.

If the demand for power exchange between two bid areas exceeds the capacity limit, it will result in separate prices in the two areas. Obviously, there will be a higher price in the deficit area and a lower price in the surplus area, and the different market participants will either gain or loose compared to an unconstrained case with one common system price. Even though the consumers in the surplus area gain from a lower price and the producers in the deficit area gain from a higher price, it can be shown that there will always be a net loss to society resulting from the congestions.

The area prices can be computed and displayed as functions of net transfer flow between the areas (interface flow) as illustrated in Fig 3.5. F_0 denotes the initial transfer demand and F_{lim} is the actual capacity limit. This net loss can be computed and illustrated graphically as the shaded area between the price curves.

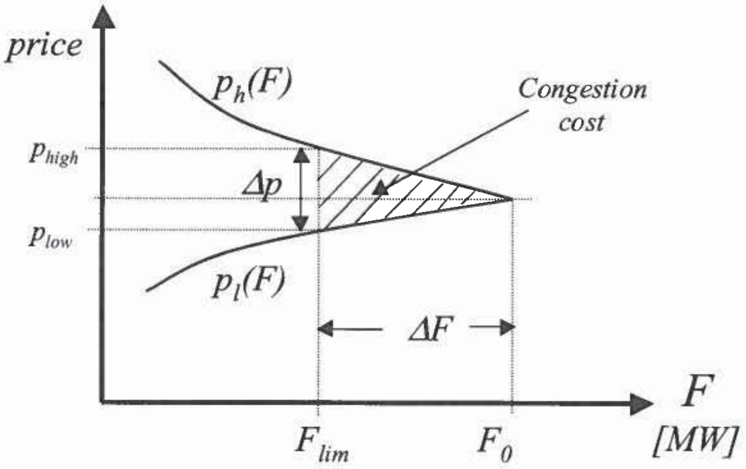

Figure 3.5 Area prices as function of interface flow.

Risk assessment, security index

The computation of cost functions relies on both market information and system descriptions (load flow and dynamic models). While the computation of congestion costs is relatively simple and straightforward, the determination of expected interruption costs require extensive computations, which involve various degrees of uncertainty. Both contingency analysis and dynamic simulations, incorporating system protection models, are generally needed in order to assess the amount of interrupted power resulting from a contingency. The uncertainties include the following aspects:

- Uncertainty or lack of required data.
- Uncertainty related to the choice and use of models.
- Uncertainty related to the choice of interruption scenarios and the risk of disaster scenarios.

In order to make the probabilistic criterion reliable in practical use, the operator must be able to assess the risk and uncertainty in a simple and understandable manner. These aspects represent important challenges for practical implementation of the proposed method.

A practical approach to risk assessment is implemented in the prototype model described in Section 3.7. Rather than attempting to compute the expected interruption costs, a risk based security index is defined as follows:

$$I_{risk} = \sum_{i=1}^{n} \lambda_i \cdot \left[\sum_j KP_j \left(\frac{\Delta P_j}{P_N} \right)^2 + \sum_j KU_j \left(\frac{\Delta U_j}{U_N} \right)^2 \right]$$

The computation of this index is solely based on steady state contingency analysis. It takes into account probabilities of contingencies (λ_i) in terms of failure rates of individual components. The severity (bracketed expression) are described in terms of individual weight functions on thermal overloads and voltage deviations resulting from the contingency analysis.

A more comprehensive description of uncertainties and risk assessment applied to this particular problem is found in the PhD-dissertation "*Flexible transfer limits in an open power market. Congestion versus risk of interruption*" [29], ref. Section 3.8.

Main conclusions

- The possibility of increasing the transfer limits in periods of fair weather conditions, and when the market transfer demand is high, could lead to significant savings in total grid operating costs, as demonstrated by case studies. In a long-term perspective, such a procedure may result in more effective utilisation of the transmission grid, and thereby avoid or postpone the construction of new lines.

- Preliminary conclusions indicate that the probabilistic method is a feasible solution to the objective. Two issues are found to be important for further development and practical implementation. The first relates to computational problems and uncertainties involved in the determination of expected interruption costs. Secondly, effective use of system protection schemes is found to be particularly important, not only as a means to reduce the actual interruption costs, but also for reducing the uncertainty related to determination of expected interruption costs.

- It is possible to introduce probabilistic methods in security assessment gradually by exploring simplified methods. It is recommended that a prototype tool is developed in order to gain practical experiences. With this tool it should be possible for the operator to assess the trade-off between congestion costs and security as a function of interface flow.

3.3 NETWORK ANALYSES IN COMBINED AC/DC-SYSTEMS

3.3.1 Objective

- ***To develop knowledge and skills in power system analysis with particular respect to modelling and analysis of HVDC, FACTS and system protection schemes.***
- ***To perform selected analyses, focusing on new components (HVDC, FACTS, etc.) and their applications and benefits in power system operation. This includes selection and location of new components and design/tuning of controllers.***

The background and main motivation for this sub project is related to the new and more active components becoming available in transmission systems. FACTS components and advanced system protection schemes have the potential to change the way transmission systems are operated. There is a need to develop tools and skills for application and assessment of the new technology.

The project has mainly focused on assessment of the new technology and new methods and tools for power system analysis. This is first of all related to design and control of FACTS devices and methods for system stability assessment.

3.3.2 Results and recommendations

Documentation:

- 2 technical reports in Norwegian [7, 8]
- 1 conference paper [9]

HVDC and FACTS – Survey of technology and trends

Status and trends with respect to development and application of HVDC systems and FACTS devices are described. Operating experiences of existing installations are documented as far as possible and the main challenges for future research and development in this field are identified.

Controls for HVDC systems

An overview of control systems for HVDC schemes is presented. This includes a description of the various controls necessary for operating a DC-link. Appropriate models for use in dynamic system analysis are proposed, including special controls for stability enhancement.

Dynamic interaction among power system controls

This activity includes a survey of methods and tools for analysis of dynamic interaction in large power systems. Available methods based on linear system analysis are described, and it is shown how information derived from eigenvalues and eigenvectors can be used to identify important system characteristics.

Participation and contribution to Cigré Task Force 38.02.16 "Impact on interaction among power system controls" has also been a part of this activity.

Small signal stability

The program system "PacDyn" for small signal stability analysis was introduced and acquired through this project. A comprehensive introductory course was organised, focusing on the use of PacDyn and practical application of small signal stability analysis.

In a joint effort with CEPEL (the Brazilian electric power research centre), PacDyn has been further developed and modified in order to handle and read the full Nordel power system model in PTI format.

Power system model reduction

It is recognised that when performing large-scale power system analysis, a very large part of the work is related to editing of input data in order to establish a realistic system model. This is further complicated by the fact that different types of analyses require different models. However, for most types of studies, a full model representation is not necessary. This activity has comprised a survey on techniques for reduction of power system models. The main objective has been to develop a practical approach on how to establish appropriate system models.

The main result from this activity is the outline of a method to create reduced order models for various types of studies based on the use of an 18-bus Nordel power system equivalent as the core model (ref. Ch. 4).

Stability analysis of the Nordel power system

Selected analyses of the Nordel power system were performed using PacDyn as the main tool. The aim of the analyses was to demonstrate the application of small signal stability analysis on a very large system model. The initial studies focused on identification and characterisation of potential stability problems in the interconnected Nordel system. Major inter-area modes and more local stability problems were successfully identified.

The main conclusion from this activity is that small signal stability analysis on this large system is both feasible and useful. The main findings from the initial analysis in terms of stability problems are verified through observations and measurements in the real system.

On-line dynamic security assessment (DSA)

New methods for large-scale power system analysis in conjunction with new tools for wide area power system monitoring opens interesting possibilities with respect to on-line dynamic security assessment.

Two different approaches are proposed. The first is based on state estimation in combination with small signal stability analysis for on-line tracking of damping and frequency of major inter-area modes and critical local modes (Figure 3.6). The second approach is based on the use of synchronised phasor measurement units (PMU). Installed at a certain number of locations throughout the system, the PMUs can be used for on-line monitoring of power system oscillations.

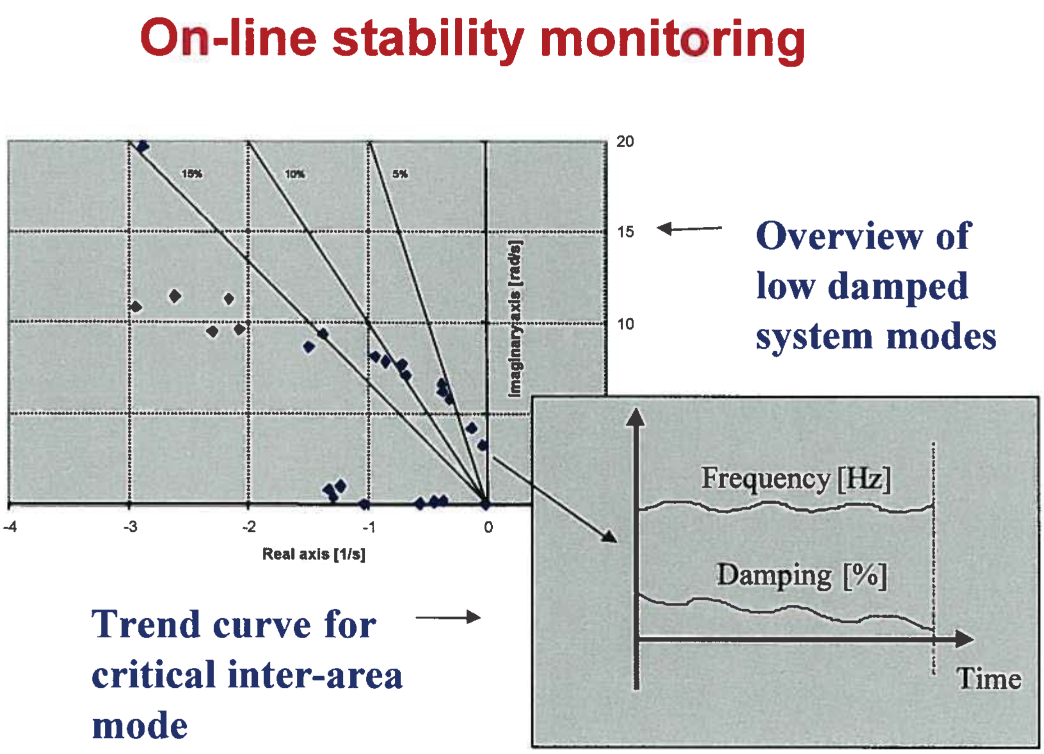

Figure 3.6 On-line assessment of power oscillations through state estimation and eigenvalue analysis.

Summary of recommendations

Based on the experiences gathered in this subproject, the following topics are recommended for further studies:

Validation and improvement of simulation models

- Continue model validation work with new measurement campaigns.
- Improve modelling of system components (load and controller models).
- Implement models for system protection schemes.

Location and tuning of power system stabilisers

- Overall system stability properties may be improved by co-ordinated tuning of power system stabilisers (PSSs)
- Detailed assessment of PSSs using small signal stability tools (PacDyn).
- Propose (re)tuning and (re)location of PSSs through a co-ordinated design approach.

Small signal stability analysis in operation planning

- Follow up the use of PacDyn and small signal stability analysis
- Establish an appropriate interface with other EMS software in order to improve the user-friendliness.

More detailed studies of methods and tools for on-line dynamic security assessment

- Further assessment of methods for on-line DSA.
- Implement PMUs for wide area monitoring in order to gain practical experience.
- Develop and implement prototype tool for on-line DSA.

New control concepts for power transmission systems

- Initiate long-term research activities exploring new control concepts aiming at more distributed control and monitoring.
- Application of software agents for control and monitoring of substations.
- Co-ordinated control and operation through communication between agents.

3.4 HARMONIC DISTURBANCES FROM FACTS AND HVDC COMPONENTS

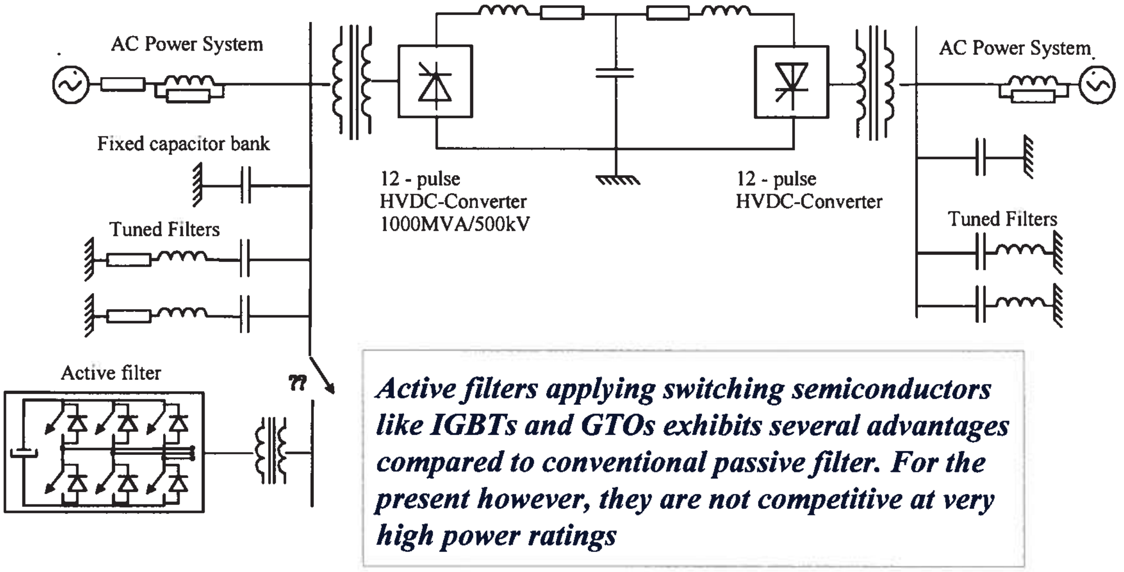

Figure 3.7 CIGRE Benchmark Model of HVDC Transmission.

3.4.1 Objective

To clarify the degree of, and to find mitigation techniques for problems related to harmonics and noise from HVDC and FACTS

The main objective and user benefit was defined at an early stage of the project, and was characterised by the need at Statnett to clarify possible problems related to harmonics from HVDC terminals, as a consequence of the additional installation of 2-3 HVDC-converters in Southern Norway. Previous operational problems in the Kristiansand HVDC station, which were assumed to be related to some harmonic interference and instability phenomena, gave reason to pay attention to the topic.

3.4.2 Results and recommendations

Documentation:

6 technical reports in Norwegian [10-15]

New technology within power electronics for realisation of various FACTS-components and active and hybrid filters, was subject for investigations at an early stage of the project. This was motivated by the extensive focus upon this issue at that time. However, investigations of new technology had to give way for a more important priority on analysis of possible harmonic problems related to the operation of conventional HVDC terminals, especially due to the fact that more terminals of the same type would be installed in the area. At a later stage of the project, more attention has been paid to the investigation of the simulation program PSCAD/EMTDC in order to reveal limitations and bugs, and to improve the program on critical points for harmonic analysis. This program was decided to be used by Statnett as the primary simulation tool for harmonic analysis in the time domain.

Although the priority of project activities has been changed during the project period, the main objective of the project has been retained. This is a brief summary of main activities and results from the project:

Survey and sorting of harmonic problems which may arise
General investigations have been carried out. Mainly based on published operational problems experienced on HVDC transmissions worldwide. Dialogs with international expertise at courses and conferences have also given valuable information. Subjects for studies have been:
- Sources for harmonic interference, interactions and instabilities
- Interaction of harmonics on AC-and DC-side of HVDC-terminals
- Especially 2. harmonic interaction and core saturation instabilities
- Harmonics and noise due to stray capacitance in the HVDC-terminal
- Effects of harmonics

Investigations of methods and tools for analysing harmonic problems
- Applicability of time domain and frequency domain analysis.
- Limitations in tools and methods
- Special investigation on applicability and limitations of frequency scan

General survey of possible solutions on harmonic problems
- General filtering and damping attempts with passive filters on both AC-and DC-side
- Tuning of control system
- Modifications of transformer magnetizing characteristic
- Feasibility studies of active and hybrid filters

Special investigation of requirements to transformer models
- Requirements when analysing harmonic problems related to core saturation instabilities
- Improved models suggested in PSCAD/EMTDC

Special investigation on requirements to line and cable models
- Requirements when analysing harmonic problems over a wide frequency range, and where unsymmetries are involved
- More accurate and robust line and cable models for broadband analyses developed, and implemented in PSCAD/EMTDC

Modelling of measuring transformers
- Development of models for current transformers and voltage transformers (both inductive and capacitive).
- Development of user-defined subroutines applicable in EMTDC.

Analyses of power supply disturbance related to variation in DC-link current
- Analysis of non-symmetrical conditions.
- Effect of variation in DC-link current.
- DC-current in AC network causing magnetic flux off-set and saturation.
- Accurate model requirements.

Guidance of PhD student related to the project (ref. Section 3.8)

3.4.3 Unsolved problems – further studies

Based on the experiences gathered in this subproject, the following topics should be considered in potential further studies:

Improvement of simulation models (PSCAD / EMTDC)
- Non-linear models. In particular modelling of magnetic saturation

More detailed studies of harmonic phenomena
- Especially where core saturation is involved

Several HVDC-links connected to the same AC-network
- Case studies of harmonic interaction problems, dependent on short-circuit power in the AC-network
- Harmonic problems initiated by commutation fault.

More detailed studies of methods for mitigating harmonic problems
- Adjustment (e.g. modulation) of HVDC control system
- Passive filters
- Active and hybrid filters
- Transformers with air-gap

Improved voltage and current monitoring in Kristiansand
- Analysis of existing monitoring system with emphasis on variables relevant for revealing the cause of disturbance.
- Modification and possible extension of existing monitoring system

3.5 ACTIVE RESERVES, FREQUENCY AND LOAD FOLLOWING CONTROL

3.5.1 Objective

To develop and test methods for provision and activation of active reserves in the Norwegian power system.

3.5.2 Results and recommendations

Documentation

- 2 technical reports in Norwegian [16-17]
- 4 conference papers [18-21]

Active reserves

The active reserves in the Nordic power system are divided in three categories:

- Instantaneous (primary) reserve, automatically activated by turbine governor droop
- Fast (secondary) reserves, manually activated from Regulating Power Market
- Slow (tertiary) reserves, manually activated from available capacity when needed

Traditionally, the hydropower dominated Norwegian system has had a satisfactory reserve situation. In the current deregulated regime with focus on corporate profit, however, this is no longer a matter of course. The last years the margins between available generation capacity and system peak load have been gradually reduced. Also, control of frequency and active power is an international problem, since all synchronised systems will experience the same frequency deviation due to imbalances or outages.

The price settlement on the Nordic spot market (Nord Pool) is made without reference to the geographic location of generation or load. Only when the different utilities submit their schedules in the evening, is the System Operator able to get a detailed overview of generation and available reserves the following day. As the time of market settlement is moved closer to the actual operating hour, the time available to the System Operator to generate his overview to detect and possibly prevent critical situations is decreasing. Thus, there is an increasing need for efficient routines, tools and possibly automatic control function in the future.

Our general recommendations to the System Operator are as follows:

- **Implement a graphic interface with overview of scheduled generation, reserves and available capacity**
- **Modify existing "Energy and Power Flow " tools (described in Ch. 4) to predict future congestion**

Frequency control and load following

One major problem during normal operation is the transition from one hour to the next, as generators normally maintain a constant load in MWh/h during the hour, while the consumption is constantly changing. As there is no automatic load-frequency control in the Nordic system, this mismatch creates a systematic deviation in frequency with positive and negative value during the hour, as shown in Figure 3.8. This problem is most critical during morning periods with heavy load pickup. As illustrated in Figure 3.9, the system frequency will decrease faster with faster load pickup, and the time available to the System Operator to activate necessary reserves to keep the system frequency within the required 49.9 Hz will decrease. A major presumption is of course that sufficient reserves are available to the system, and are not limited by grid bottlenecks.

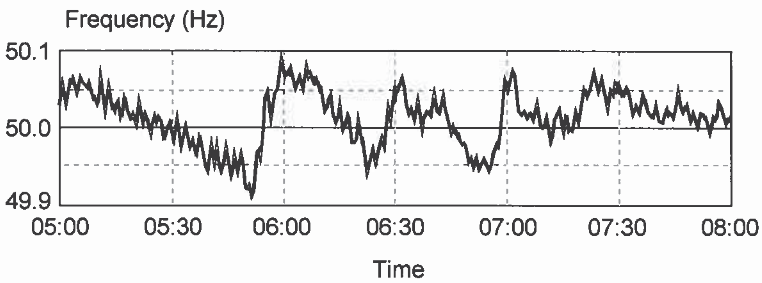

Figure 3.8 Frequency deviation due to mismatch between generation and load

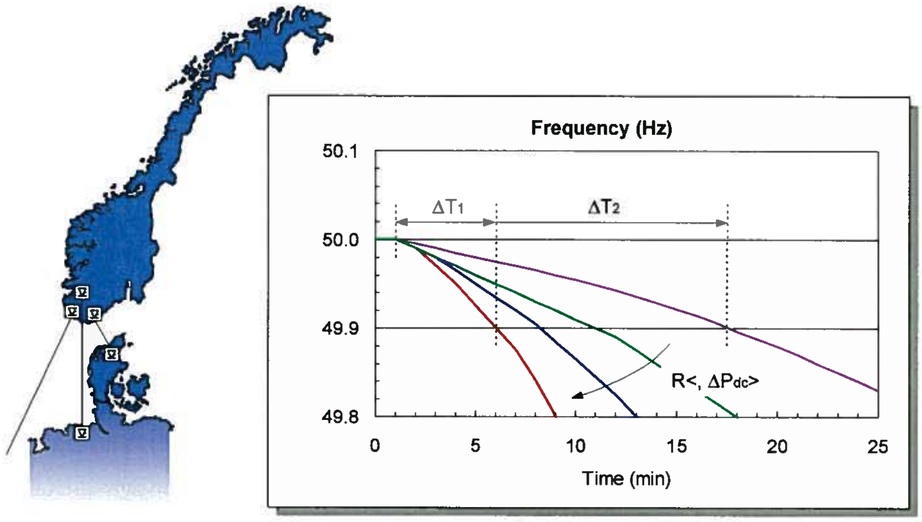

Figure 3.9 Reduced time margins due to increased system strain

By assuming linear droop control, Figure 3.9 can be inverted to show how fast the system frequency will drop as a function of frequency bias. In Figure 3.10 the relation between frequency bias and different levels of load increase is shown for a frequency deviation of -0.01 Hz. The current response requirement for regulating power is 15 minutes. Figure 3.10 shows that if the load ramp exceeds approx. 150 MW/min, an increased frequency bias will not be sufficient to keep the system frequency within 49.9 Hz for 15 minutes. However, improving the System Operator's abilities to supervise and provide sufficient reserves might still not be enough, as long as the activation of reserves is based on manual request and control. Introducing automatic control functions is then a possible alternative.

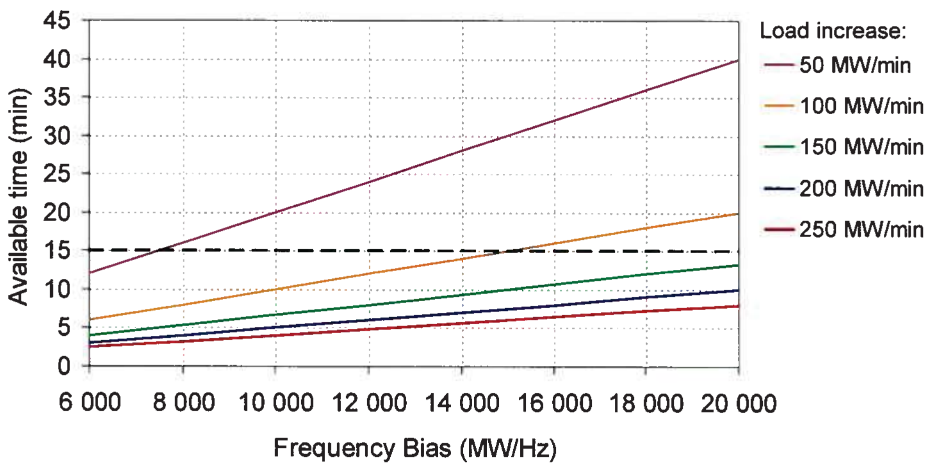

Figure 3.10 Available time to keep system frequency above 49.9 Hz

To enable the System Operator to predict the frequency deviations during load pickup and simulate the amount and location of necessary reserves, a methodology termed *Incremental Load Flow* (IncrLF) has been developed. *IncrLF* uses stationary load flow algorithms to simulate slow system dynamics in the minute area, and is briefly described in Ch. 4 *Tools and models*. The *IncrLF* is linked to the data submitted daily to the System Operator from the utilities though a prototype graphic interface to increase the operator's overview and enable him to take necessary action in the case of insufficient or unfavourably distributed reserves. This interface is briefly described in Ch. 5 *Visualisation of power system data*.

The handling of larger and faster load changes are expected to become more and more critical in the future. Improving the System Operator's abilities to supervise and provide sufficient reserves might not be enough, as the activation of reserves is still based on manual request and control. Introducing automatic control functions is then a feasible solution, providing the control scheme is designed to retain the decentralised market structure where all parties can participate on a commercial basis. This is possible through a combination of control communication and web-based techniques, and can be introduced in two steps. The first step can be a dedicated load-following scheme where generating units automatically follow major system loads, as shown in Figure 3.11. This scheme can be further developed to a fully international, market based AGC.

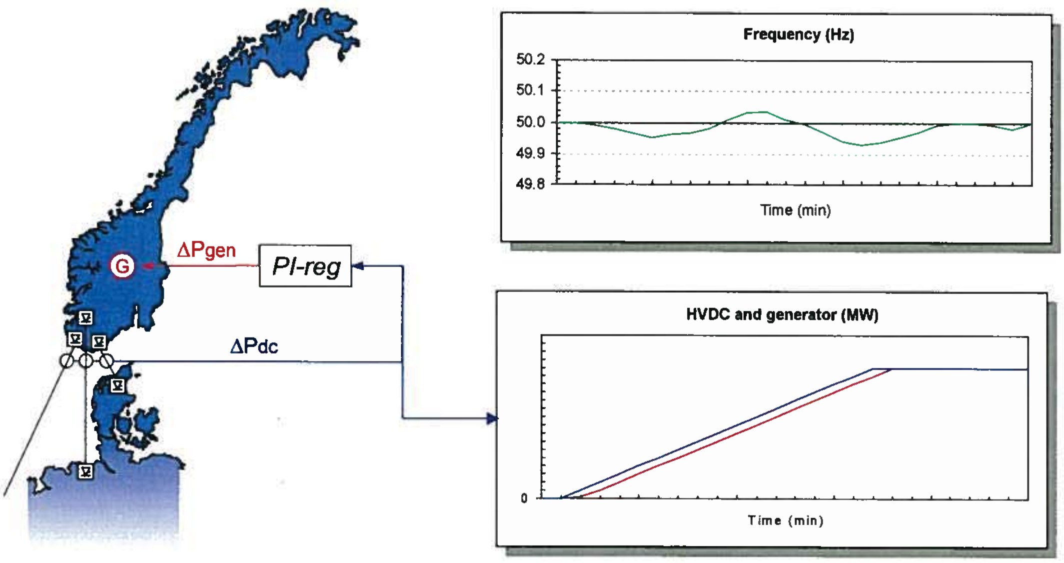

Figure 3.11 Load following control scheme

Recommendations: - **Implement "Incremental Load Flow" tools to simulate activation of reserves during critical periods and contingencies** - **Implement automatic load following controllers for major system loads**

3.5.3 Further studies

Based on the experiences gained in this project, the following topics should be the focus of further studies:

- **Evaluation of the consequences of a unified, international Nordic control area where frequency and time deviation are the only global control criteria**
- **Design and testing of algorithms for optimal activation of control objects based on marginal losses and sensitivities**
- **Design and testing of fully automated market based secondary control**

3.6 VOLTAGE STABILITY ASSESSMENT, TOOLS AND MODELS

3.6.1 Objective

- ***To evaluate tools suitable for effective on- and off-line analyses of voltage stability.***
- ***To test component and network models (static and dynamic) and gain experience of data and parameter sensitivity.***

As a consequence of major reactive consumption in HVDC transmission, voltage problems in the terminal area should be paid special attention. In the Hasle interface (AC) between Eastern-Norway and Sweden voltage stability is a main concern and limiting factor. Monitoring of reactive balance and distance to voltage collapse will become more and more important part of safe system operation.

An efficient model for voltage stability assessment will be useful for the operators. Knowledge of the distance to voltage instability allows operation closer to limits and provides more accurate information for preventive and corrective measures.

3.6.2 Results and recommendations

Documentation

- 4 technical reports in Norwegian [22-25]

Definitions

Since voltage instability takes different forms and involves many phenomena and time constants, it is challenging to give a precise definition. However, the following definitions are used in the industry:

Small-disturbance voltage stability: Following any small disturbance, voltages near loads are identical or close to the pre-disturbance values.

Voltage stability: Voltages near loads approach post-disturbance equilibrium values. Voltage instability results in progressive voltage decrease (or increase).

Voltage collapse: Post-disturbance equilibrium voltages near loads are below acceptable limits. Voltage collapse may be total (black out) or partial.

Modelling

Voltage instability is a dynamic phenomenon. Still static methods are sufficient in many cases.

The following requirements should be paid special attention:
- **Stationary and dynamic response of aggregated loads.**
- **Areas with major motor loads**
- **Short term overloading ability should be modelled**
- **Modelling of reactive production should exceed normal operation area**
- **Transformer tap changing control**

Methods and tools

Dynamic simulation:

Since voltage stability is a dynamic phenomenon, the dynamic simulation is the only tool that can give the true response due to a disturbance. However, dynamic simulation has some features that can not be ignored:

- The simulation approach is time consuming and most commercial programs are not suited for studies over the adequate time periods. Special mathematical formulations are required.
- It may be a challenge to address the problem. A lot of information is available and it may be difficult to extract the right information.
- Detailed and consistent component models are required.

Stationary and quasi stationary analyses:

These methods use a simplified model of (or in some cases completely ignore) the dynamic response and can not be used to study transient voltage stability. However, since many voltage stability problems involve transformer tap changing and load increase, such techniques are used to estimate system robustness to long-term voltage stability problems.

Either regular load flow programs or special formulations as continuation power flow is used for such analyses.

Modal analyses:

Modal analysis is a useful tool for voltage stability analysis. The eigenvalue and the eigenvectors of a matrix can be used to extract important information about modes in the systems. A mode is strongly connected to the degree of stability. These techniques can be combined with both the static and the dynamic methods to study interaction between parameters.

Data requirements

The methods for voltage stability analysis do have different data requirements. The most accurate methods like dynamic simulation need the most detailed and consistent models.

It is a general experience from this project that models of loads and to some extent of reactive production and control are too rough in available data.
Field measurements in order to tune vital parameters are highly recommended.

Corrective and preventive measures

The possibility to intervene in a process moving against the voltage instability is important. In order to do that, the operator needs tools that alerts about the coming situation. This is a challenging task. However, there are some standard techniques to avoid uncontrolled instability.

Examples of corrective actions:
- **Blocking of the tap-changers on transformers to avoid an uncontrolled load restoration after an initial disturbance.**
- **Load shedding e.g. tied to maximum transfer on transmission corridors.**

Examples of preventive actions:
- **In transient voltage instability case to ensure that all short-term capabilities of reactive support is available to avoid motor stalling.**
- **Rescheduling of production to avoid the consequences of a single contingency.**

Examples

In [25] six examples of voltage instability are given. These examples cover both short-term and long-term voltage instability and different methods are used to study the cases. In Figure 3.12 an example of voltage profile in the 420 kV system in the Oslo-area referred to the transmission in the "Hasle-corridor" on the border to Sweden is displayed.

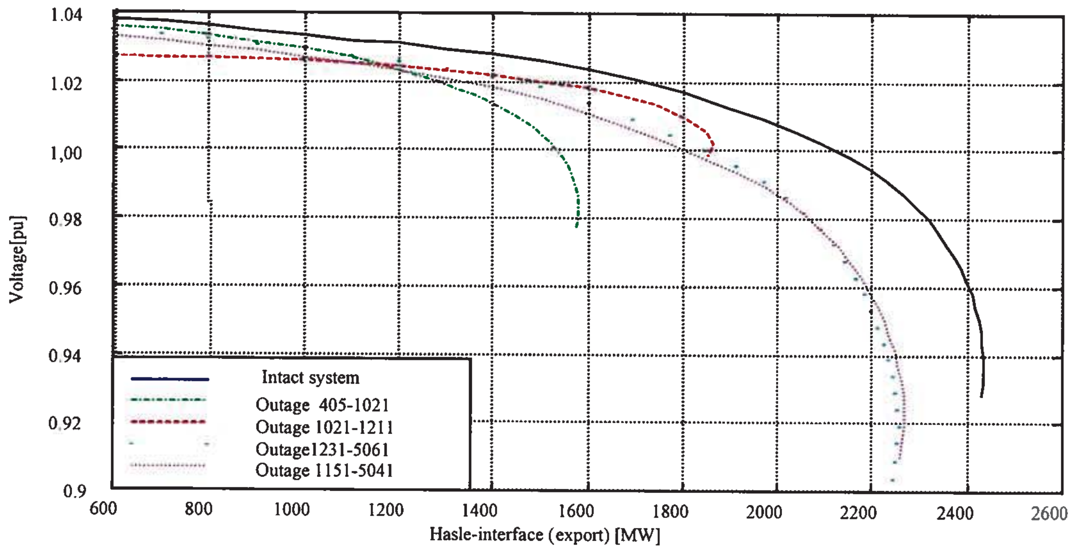

Figure 3.12 Voltage profile 420 kV Rød

Recommended tools in National Control Centre

In the initial delivery of the tools for the control centre there will be load flow programs available for studying long-term voltage instability. Though there are some limitations with these tools from the dynamic aspect, they may be very useful as a starting point for doing such studies. The results are easy to understand without any deep mathematical background. The data requirements are also according to standard network analysis and should be available.

However, it is important to proceed with the development, integration and application of new and enhanced tools for studying the accurate system response. It will also be useful to study the interaction between system parameters and the impact on critical voltage instability modes in the system.

The goal should be to have the adequate tools available and integrated in the same environment to facilitate complete studies of the voltage instability phenomena.

3.7 ON-LINE APPLICATIONS NATIONAL CONTROL CENTRE

3.7.1 Objective

- *Develop tools/concepts proposed in subprojects 2, 5 and 6 for on-line applications in the National Control Centre (NCC)*
- *Improve utilisation of advanced tools in decision support based on operator specification.*

System operation close to physical limits requires more efficient tools and models in the main control centres. The need for new tools is discussed in this sub project, based on a description of the main tasks carried out in the NCC. However, the main part of the project is dedicated to further development of models proposed in sub project 2, 5 and 6:

- Model for flexible transmission limits
- Model for active reserve monitoring
- Model for voltage control

3.7.2 Results and recommendations

Documentation

- 2 technical reports in Norwegian [26-27]
- 1 conference paper in Norwegian [28]

Control structure

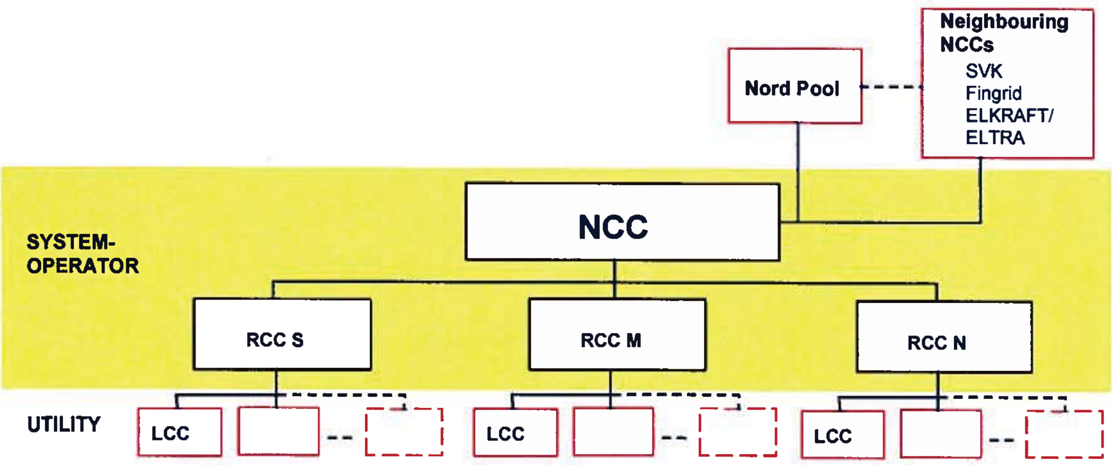

Figure 3.13 Control structure in the Norwegian power system

Figure 3.13 shows the structure of the Norwegian power system control. Statnett as System Operator has the responsibility of the National (NCC) and Regional (RCC) levels, which communicate with the Local Control Centres (LCC), the neighbouring NCCs and Nord Pool.

New tools in NCC

Statnett has purchased new tools for energy management (EMS). The contract partner is ABB and the system includes new computer systems for remote control in three Regional Control Centres and study and real time EMS functions in the National Control Centre. The installation of the new systems will be completed at the end of 2001.

Table 3.1 New EMS tools in NCC

Tasks & tools	Study	Real time
State estimator		x
Dispatcher Power Flow	x	
Optimal Load Flow	x	(x)
Contingency analyses	x	x
Reserve computation	x	x
Voltage Scheduler	x	
Voltage collapse analyses	x	x
Transfer limit calculation	x	x

Need for decision support tools

As mentioned earlier, several factors indicate that the pressure on power system operation will be increasing the coming years. Table 3.2 sums up our view of how decision support tools might improve the efficiency of the operator work.

Table 3.2 Tasks and tools

Task	Expected change	Need for decision support
Network utilisation	Operation closer to thermal limits	- Contingency analyses - Probabilistic security assessments
Frequency control	Shorter time available for secondary control	- Active reserve monitoring - Forecasting of frequency deviations
Voltage control	Shortage of reactive power will occur more often	- Reactive reserve monitoring - Optimal load flow - Margin to voltage collapse calculation

Prototype: Flexible Transfer Limits calculation

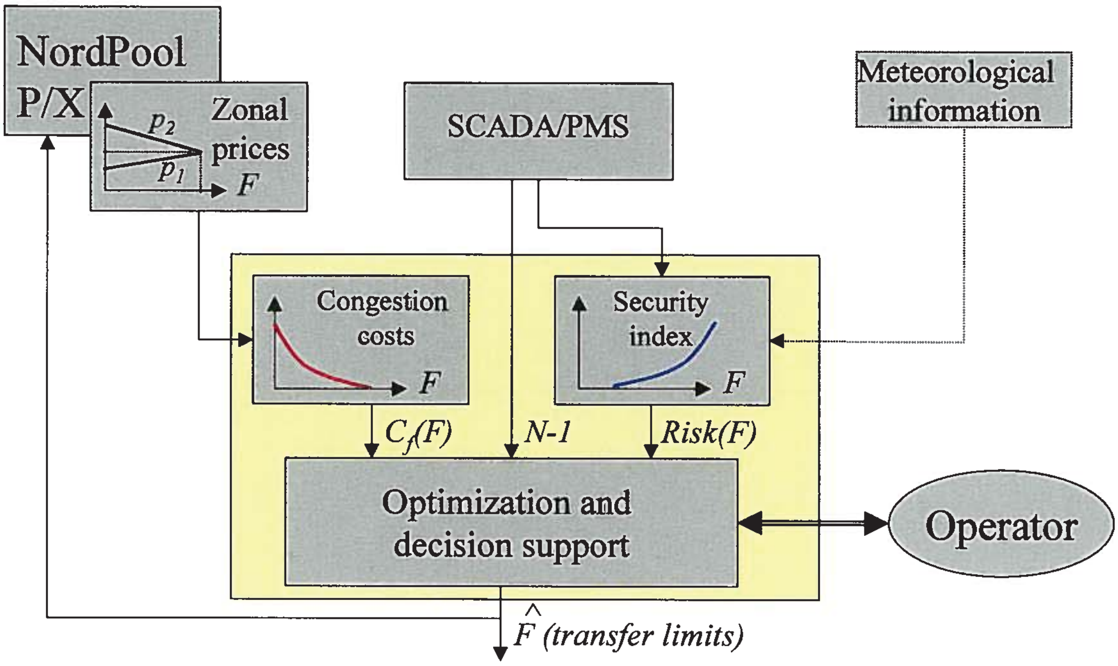

Figure 3.14 Prototype flexible transfer limits

The prototype illustrated in Figure 3.14 is based on the principal work in sub project 2, which is reported in chapter 3.2.

This model is designed as a decision aid tool in the NCC to enable the operator to redefine transmission limits during operation. The concept is based on minimisation of the socio-economic congestion costs, with the security index as a restriction. The figure refers to a zonal approach to congestion management, but the concept is also covering the Buy Back (or Counter Trade) model, which also is applied in the Nordic system.

The Nordic spot market (Elspot) is divided into several price zones. The System Operator defines the transfer limits between the zones. Normally the transfer limits are defined for one week at the time.

The idea of this prototype model is to allow the System Operator to adjust the transfer limits before final settlement of the zonal prices in Elspot, based on information about the consequences of the predefined transfer limits. This information includes socio-economic congestion costs, as a function of shortage of transmission capacity, provided by the Power Exchange (Nord Pool), and security indices based on contingency analysis. If the gradient of the congestion cost is steep, even small changes in the transfer limit would result in profit to the society (reduction in difference between the zonal prices). The change of transmission limits would be acceptable also from a security point of view if the gradient of the security index function remains low e.g. as a consequence of improved weather forecasts.

Prototype: Active reserve monitoring

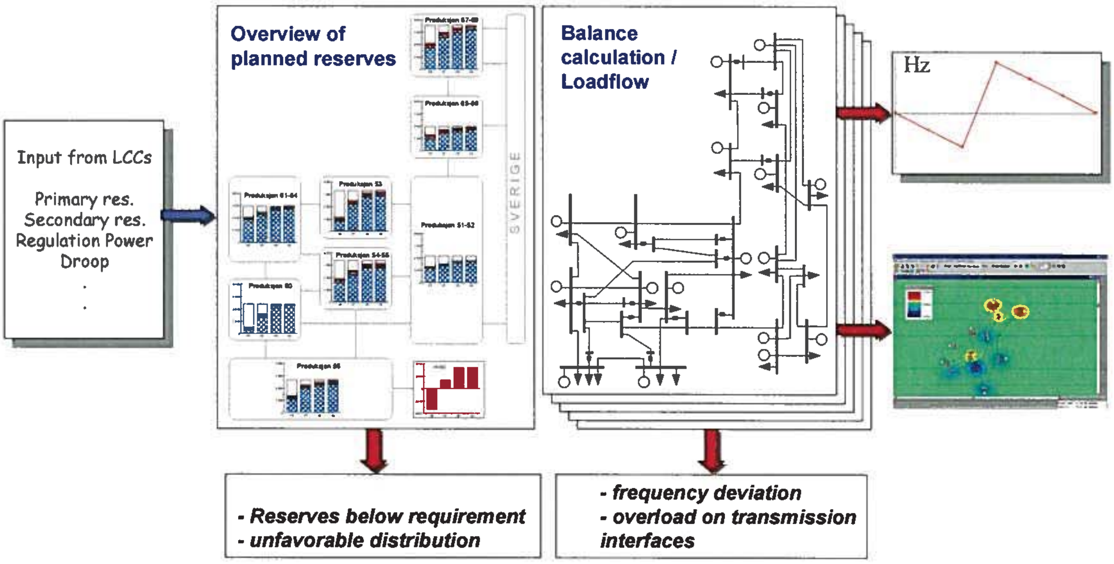

Figure 3.15 Prototype active reserve monitoring

The integrated model for active reserve monitoring in Figure 3.15 is based on research carried out in sub project 5, reported in chapter 3.5.

The model has three primary functions:

- Inform the NCC operator of the reserve situation in total and in predefined sub control areas.

- Enable the operator to analyse the distribution of the reserves by doing load flow analyses to detect consequences of frequency drops caused by “dimensioning fault”.

- Enable the operator to forecast the need for secondary control in periods with steep loading curves. The analyses are carried out by running an “Incremental Load Flow” program as described in Section 3.5.

Visualisation of results is a vital part of this model as indicated in the figure. At this prototype stage only illustrations of visualisation are made and further development requires more efforts on this important subject.

Model for voltage control

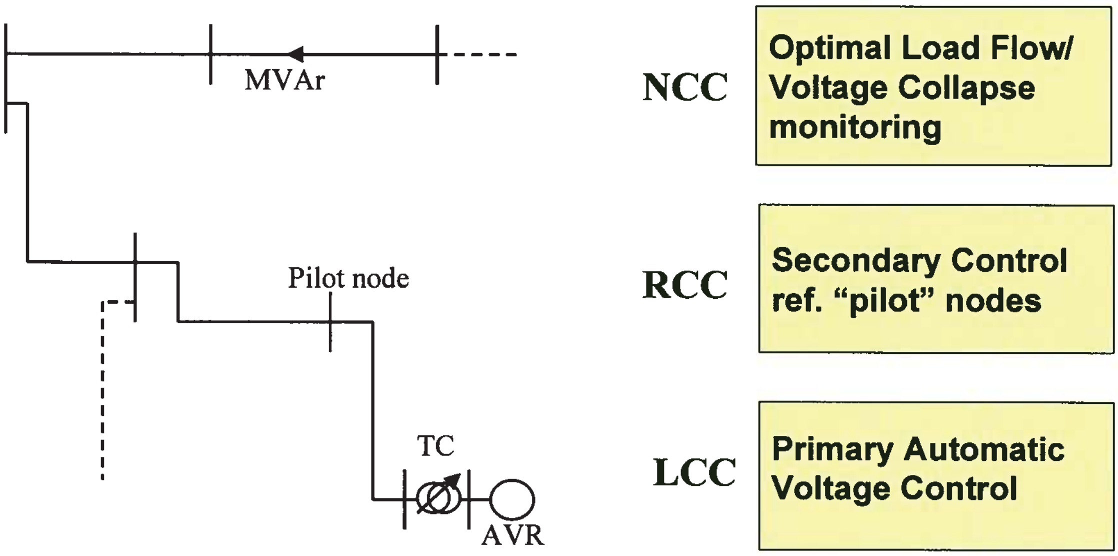

Figure 3.16 Multi-level voltage control

An efficient voltage control scheme is needed to take advantage of advanced tools. A multi-level voltage control model as illustrated in Figure 3.16 is proposed for the Norwegian system. The model is based on similar models adapted in France and other European countries. The RCC is responsible for main grid voltage control and the reactive reserves in the system, while the NCC calculates and recommends the voltage profiles and supports the RCC with EMS- analyses.

The basic idea of this model is that voltage control is referred to limited zones and to selected "pilot nodes" within each zone. Control zones for voltage control in Southern Norway and pilot nodes are proposed as a part of this project.

The functionality of this model is demonstrated on a real low voltage situation in the Oslo area last winter. Decreasing voltages were detected at the RCC and load shedding was considered. The example presented in [27] shows how EMS-analyses at the NCC in that case could have provided information of distance from voltage collapse and safe operational limits.

3.8 PhD SUBJECTS

Three PhD students have been associated to the project.

1. ***Flexible transfer limits in an open power market. Congestion versus risk of interruption.***
   Dr.ing. Geir Warland defended his doctor dissertation [29] in March 1999. Additionally, two international papers have been published [30, 31].
   Main supervisor: Professor Arne T. Holen.
   A new approach to determine operating limits for critical transmission corridors is presented and discussed. The case is formulated as a multi-objective decision problem. The two particular objectives implemented are minimisation of operating costs, including congestion costs and interruption costs, and a security index measuring vulnerability to voltage collapse. Various types of uncertainties are represented and included in the problem, soft constraints are represented by fuzzy numbers, and the risk of making a regrettable decision (for operating limits) resulting in large operation costs or unacceptable power blackouts is specifically taken into the problem formulation.

2. ***Voltage instability with particular emphasis on instability prediction based on local area measurements.***
   Candidate: Leif Warland. Planned defence for doctor dissertation during fall 2001.
   Main supervisor: Professor Arne T. Holen.
   The particular core part of this research will be a discussion of the possibilities to continuously monitor and predict vulnerability to voltage instability based on local measurements supported by some information from neighbouring buses. Most commonly voltage instability predictions are based on system wide calculations, for example using "Continuation power flow technique". The approach discussed in this research is an alternative more practical for continuous monitoring.
   This work is done in close contact with the project team from ABB Corporate Research, SINTEF Energy Research and Statnett SF exploring and testing the so-called VIP (Voltage Instability Predictor) concept using measurements from a pilot installation in the main grid.

3. ***Power electronics in the power system.***
   Candidate: Ian Norheim. Planned defence for doctor dissertation during spring 2002.
   Main supervisor: Professor Tore M. Undeland.
   The main subject of this research is harmonic phenomena in operation of traditional HVDC systems. A particular phenomenon called core saturation instability is focused. By means of PSCAD/EMTDC- simulation this phenomenon and actions to prevent it are studied. Due to requirements of cost it is solutions in the control system of the HVDC converters that are most likely to have any practical implementation. Control strategies that prevent core saturation instability and at the same time does not have any other significant influence on the operation of the HVDC system will be the best solution. A suggested control strategy that seems promising is now being studied. It is very likely that this control strategy can be used to prevent other harmonic phenomena as well, but this is yet to be studied.

4 TOOLS AND MODELS

During this project numerous commercial and non-commercial analytical tools and models have been used. The project group has gained wide and comprehensive experiences on the different available tools, including internal algorithms, user specific design and component modelling. Also, in cases where available tools have been insufficient for the specific task, new methods and models have been developed.

4.1 EXISTING TOOLS AND MODELS USED IN THE PROJECT

The following existing tools and models have been used for a number of purposes in this project:

PSS/E - *stationary and dynamic analyses*
- studies of control concepts
- controller design and implementation
- fault analyses

SIMPOW - *stationary and dynamic analyses*
- voltage stability analyses
- controller design and implementation

EMTDC - *transient analyses of power electronic devices*
- harmonic interactions in HVDC terminals

PacDyn - *linear analyses*
- small signal stability and inter-area oscillations
- controller design

SECOPT - *Security Constrained Optimisation*
- sensitivities and marginal losses
- optimal selection of active reserves

Continuation Power Flow - *Quasi-stationary load flow analyses*
- voltage stability analyses

SAMLAST - *market and power flow model*
- reserve allocation
- prediction of bottlenecks

4.2 NEW TOOLS AND MODELS DEVELOPED IN THE PROJECT

When available tools have been insufficient for the specific task, new methods and models have been developed in this project. Due to the novelty of these methods, they are described in more detail than the available tools in the previous section.

4.2.1 18-bus model of the synchronous Nordic power system

To enable long-term simulations of secondary control and AGC functions, a simplified 18-bus representation of the synchronous Nordic power system has been developed in PSS/E. The model represents the major generation and load areas and tie line interfaces in the system, and is tuned both stationary and dynamically for two major load situations. The structure of the model is shown in Figure 4.1.

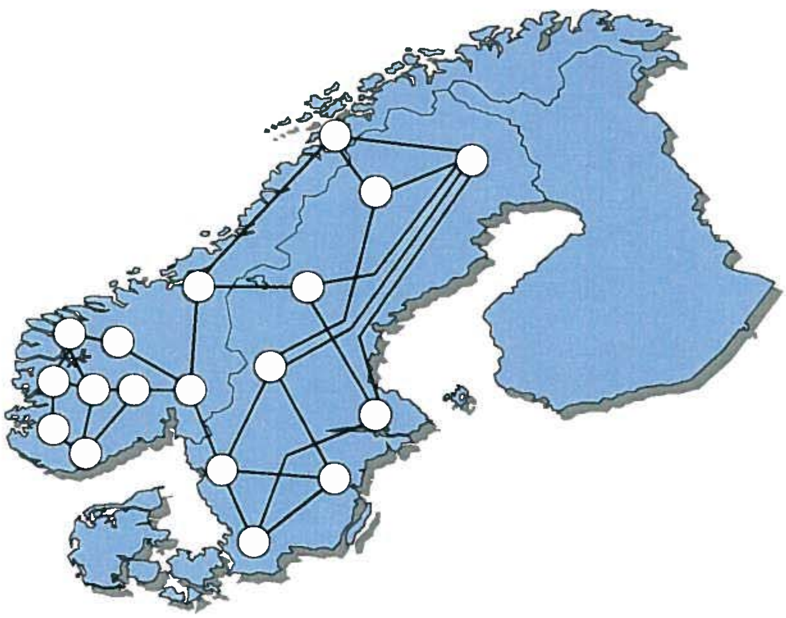

Figure 4.1 18-bus model of the synchronous Nordic power system

4.2.2 PSS/E user models

To enable development and testing of AGC functions in the Nordic power system (18-bus model), the following PSS/E user models have been developed:

ACELOG	- Measuring model that calculates the Area Control Error (ACE) of two areas and makes these available for plotting
AGCGOV	- Turbine governor (HYGOV) modified for superior AGC-control
LFC_1/2	- Load-frequency controller (LFC) for case with two areas (generators) exchanging power across a single tie-line (test model
LFC_M1/2	- Generic load-frequency controller (LFC) for two areas with multiple tie-lines and multiple generators
LOADT	- Time dependent load ramp
LOADFD	- Time and frequency dependent load ramp
MANGOV	- Turbine governor (HYGOV) modified for MANUAL changes of set point
RFC_1	- Uncompensated ramp following controller (RFC) for case with single load and single generator (test model)
RFC_2	- Ramp following controller (RFC) with droop compensation for case with single load and single generator (test model)
RFC_M	- Generic ramp following controller (RFC) for multiple loads and multiple generators

All models are prototype models designed to study specific power system phenomena. They are not systematically tested for commercial use. The models are generally useable in all PSS/E simulations, with the exception of the load-frequency controllers *LFC_x* and *LFC_Mx*, which can only be used in cases with two interconnected areas.

4.2.3 Incremental load flow

To enable the System Operator to predict the frequency deviations during load pickup and simulate the amount and location of necessary reserves, a methodology termed *Incremental Load Flow* (IncrLF) has been developed, see Figure 4.2 *IncrLF* uses stationary load flow algorithms to simulate slow system dynamics in the minute area. The system load is assumed to increase linearly during the hour, and is increased in steps while scheduled generation is kept constant. For each step, the mismatch between scheduled generation, load and losses is divided among generating units according to their droop settings. The activation of spinning reserves and its influence on power flows, as well as estimated frequency deviation can then be simulated e.g. for each 10 minute period. The *IncrLF* can also be supplemented with algorithms for activation of fast reserves and contingency analyses.

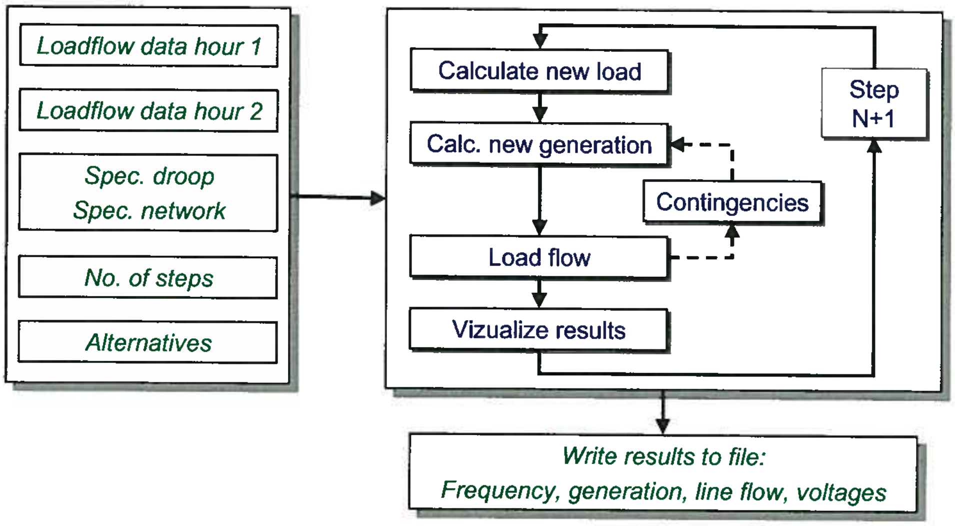

Figure 4.2 Block diagram of Incremental Load Flow (IncrLF)

The *IncrLF* is linked to the data submitted daily to the System Operator from the utilities though a prototype graphic interface to increase the operators overview and enable him to take necessary action in the case of insufficient or unfavourably distributed reserves. This interface is briefly described in Ch. 5 *Visualisation of power system data*.

4.2.4 PacDyn enhancement

In a joint effort with CEPEL (The Brazilian electric power research centre), PacDyn has been modified and enhanced to accommodate specific needs in this project.

A capability of reading PTI-formatted input data has been implemented, and several new controller models are developed. The program has been modified to handle larger system models, and successful analyses are carried out using the full Nordel system model, comprising approximately 1000 generators.

5 VISUALISATION OF POWER SYSTEM DATA

In this project visualisation has been a small, but significant part of some of the sub projects. Our approach to this subject is documented in a technical report [26]. A short summary of this report is included in this chapter.

5.1 INTRODUCTION

The basic benefits of visualisation come from exploiting fundamental and powerful human abilities to recognise patterns and relationships presented in pictures more quickly and more accurately than from sets of numbers.

Visualisation as a user interface communications medium has some associated costs and potential drawbacks. These include accuracy, processing time, hardware costs, programming costs and bad visualisation techniques.

In an EMS application, it is important that the visualisation not only informs the operator, but also directly *assists* the operator in his or her engineering tasks. Generally, the following three guidelines should be followed:

- **natural encoding of information**
- **task specific graphics**
- **no gratuitous graphics**

A problem within the power industry is that neither developers nor users of commercial EMS applications are very interested in visualisation as a scientific issue. This results in small resources and the lack of systematic research on visualisation for EMS purposes. Current research is thus located at smaller units presenting their own ideas and concepts, but not a complete design of an effective operator environment. Neither are any standard or systematic tests of the efficiency of visualisation techniques developed to measure and compare the usefulness of such techniques in supporting the operator's tasks.

5.2 USER INTERFACE SAMPLES FOR THE NORDIC POWER SYSTEM

During development of online methods and tools in this project, visualisation has several times been an issue of discussion. As an illustration of how an interactive graphical user interface can improve the handling of data already available to the System Operator, a simple prototype was developed in MS Excel using Visual Basic. Even though the interface is limited by the 2-dimentional scope of Excel, it clearly shows that useful EMS interfaces can be developed without any specialised software.

Figure 5.1 shows the main screen of the *Excel Active Reserve Interface*. This screen displays information about scheduled generation, rotating and fast reserves and available capacity in selected system areas for each hour the next day. The user can enlarge or edit the graphs to study critical hours or areas in more detail. Figure 5.2 shows an example of the full graph for one selected area.

The main screen only presents static data already available to the System Operator. From this screen, however, the user can go to other screens showing load flow and transfer limits. These screens are again connected to external calculations like *IncrLF*, which enable the user to simulate load changes, contingencies, reserve activation etc. in more detail based on the scheduled data for tomorrow.

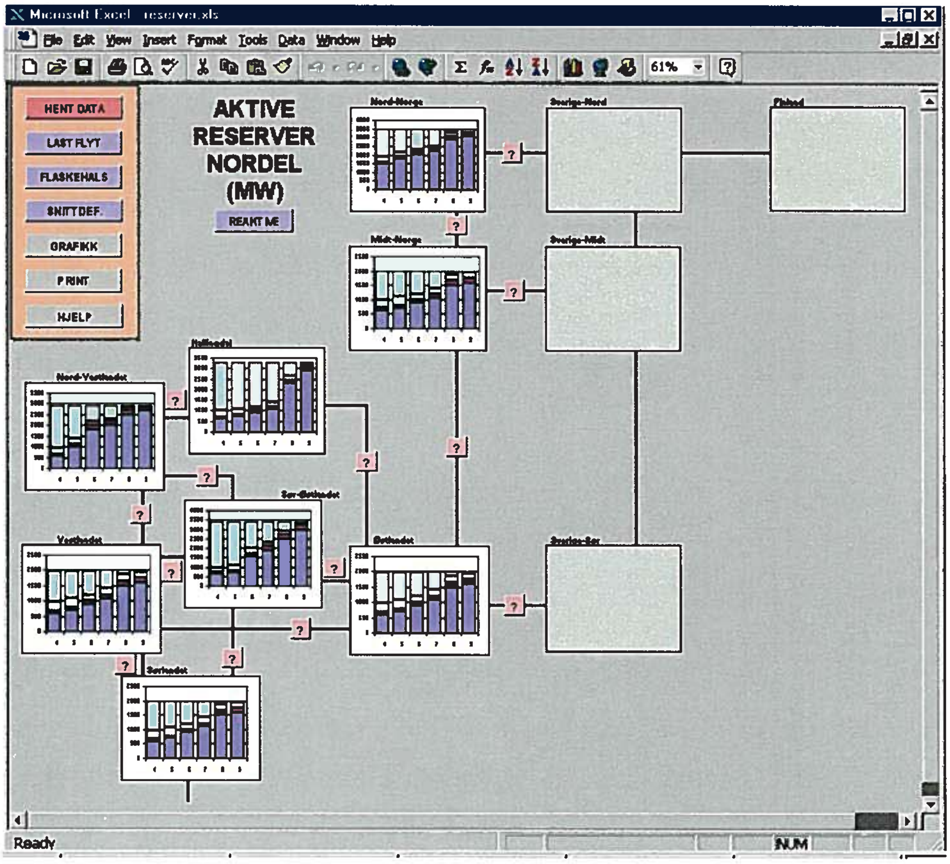

Figure 5.1 Active reserve interface in Excel

The commercial program *PowerWorld* goes one step further in visualisation while still maintaining the "classic" single line diagrams known by operators. The basic idea of PowerWorld is to use colour gradients known from other areas like meteorology to visualise voltages, load flow and generation levels. Figure 5.3 shows an example of the technique used on a simplified model of the Nordic power system. The use of red colours (hot) to signal high voltages and blue (cold) for low voltages fits well into the previous comments on "natural encoding" by creating an intuitive interpretation of the system voltages. Simultaneously, the colour contours give the user an overview of the voltage profile of the system, which would be nearly impossible to achieve by numbers alone.

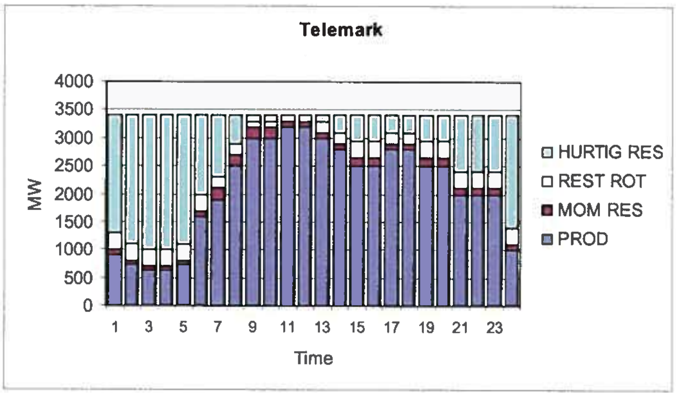

Figure 5.2 Complete graph of scheduled generation, reserves and capacity for area "Telemark"

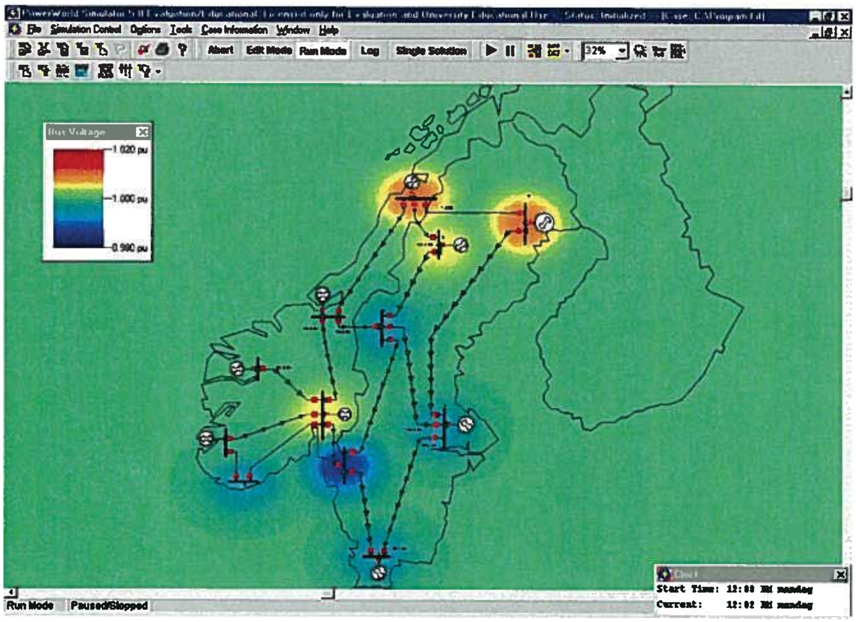

Figure 5.3 Simplified model of the Nordic power system shown in PowerWorld

Other approaches to power system visualisation can be found in the literature, which use different levels of abstraction from the "classic" single line diagrams.

The general impression of the authors is that scientific visualisation has a great potential for effectively supporting the System Operator's daily tasks. However, to reach a level of actually implementing these techniques in EMS applications, a far more comprehensive and co-ordinated research is needed. This scientific topic will probably not receive sufficient attention or resources until the EMS users themselves start demanding more advances user interfaces.

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