Implementation of a probabilistic security assessment tool for determination of power transfer limits

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SUMMARY

This paper describes the concept of a probabilistic security assessment tool for evaluation of power transfer corridor flow limits. The concept has been implemented in a computer prototype tool to aid the system operator in determination of operating transfer limits. The established prototype shows a feasible way of computing congestion costs and a risk index for security assessment based on system price information and representative load flow files. Based on the results from the computations the system operator can evaluate the consequences of increasing/decreasing PTC limits with respect to both congestion costs and the violations of voltage and branch load limits in the transmission system.

Keywords: Power system security, transfer limits, congestion cost, risk index, interruption cost.

1. INTRODUCTION

Considerable efforts have been made during the recent years to increase transmission capabilities in the Norwegian power system. A main objective is to increase power transfer limits on transmission corridors that frequently constitute bottlenecks. The efforts have focused on operational procedures, system control and inexpensive grid improvements rather than expensive and often controversial grid reinforcements. The overall motivation is to enable increased utilisation of the grid and still retain a sufficient level of security in operation.

The ongoing work has comprised a range of activities, including:

- Investigations on probabilistic security criteria enabling flexible transfer limits [1].
- Active use of system protection.
- New control centres with advanced EMS tools.
- New devices for on-line monitoring of load flow and stability properties [2].
- Investigations on tuning and implementation of new control devices for stability improvements [3].

This paper focuses on security criteria and the development of a new computer tool to aid the system operator in determination of power transfer limits. The work is motivated from an assumption that the traditional (N-1) criterion is too rigid for determination of operating capacity limits, giving unnecessary high congestion costs as a result.

Statnett SF – the Norwegian Power Grid Company and SINTEF Energy Research have during the last years worked to implement probabilistic methods to enable more flexibility in determination of power transfer limits, [1]. Results from this work are currently being implemented in a computer tool, which can assist the system operator when setting the transfer limits. The objective of the prototype is to use information from calculations of congestion costs and information from contingency analyses to identify the cost and the risk related to a chosen power transfer limit.

The paper is organised in four main sections. In chapters 2 and 3 the overall background for developing the prototype is presented. Chapter 4 gives a description of the structure of the prototype, and a brief description of the computation of congestion cost and a risk index, respectively. In chapter 5 some results from a case study are presented to illustrate the use of the computer tool.

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2. CONGESTION MANAGEMENT

The Nordel power system comprises the interconnected power systems of Sweden, Finland, Denmark and Norway. While there is a mix of hydro and thermal power generation within Nordel, the Norwegian power system is characterized by highly distributed hydropower generation. The deregulation of the electricity markets and the geographical differences in generation create an increasing demand for power exchange between parts of the system. In addition to an increasing total demand for electricity, this has lead to larger and more frequent variations in load flow patterns. In this situation the system operators face great challenges in both planning and operation of the system.

Overall power system security is a main responsibility for the transmission system operators (TSOs). The main transmission grid in Norway is operated and largely owned by Statnett SF. A common practice regarding handling of power system security is to determine operating limits on power transfer capacity on a set of (more or less pre-defined) critical transmission corridors. A *power transfer corridor (PTC)* is defined as a set of circuits (transmission lines or transformers) separating two parts of the power system (closed interface), or a subset of circuits exposed to a substantial part of the transmission exchange between two parts of the system (open interface). In this context, the power flow on a PTC represents the net power flow from a sending end area to a receiving end area. Traditionally, Statnett has applied the deterministic (*N-1*) criterion as the main operational security criterion. The (*N-1*) criterion is a simple, technical criterion which states that the system should be designed and operated in such a way that it is able to withstand any single contingency, e.g. outage of a line or generator, without resulting in unacceptable consequences.

The enforcement of PTC limits, either through market arrangements (price areas, counter trade) or corrective controls, leads to transmission congestions. The spot market of the Nordic power exchange (Elspot) is based on zonal pricing, as illustrated in figure 1. When congestions occur due to transmission constraints, this will result in price differences between different areas. In total, the price differences have a negative economic impact on participants (generators and consumers) in the electricity markets. In addition to direct costs of redispatch for handling local or unexpected bottlenecks during operation, this constitutes congestion costs.

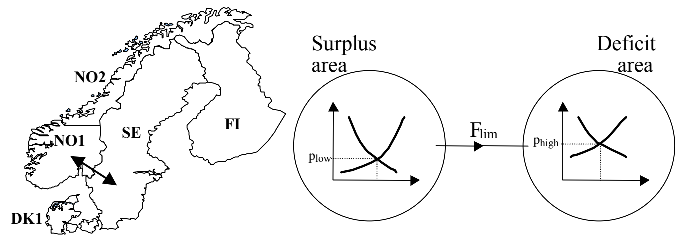

Figure 1 The concept of zonal pricing in the Nordic power system

As an attempt to avoid or reduce these costs, there has been focus on developing methods to promote a more efficient and flexible utilisation of the main transmission grid. The main objective for implementing such methods is to enable flexible limits for power transfer between areas, in a manner that does not lead to unacceptable risks.

The determination of PTC limits is an established part of the operating procedures at Statnett's National Control Centre. In general, this can be formulated as an optimisation problem with the object to minimise the total grid operation cost – consisting of congestion cost, C_C and expected interruption costs, C_{EIC}, [1] as illustrated in figure 2.

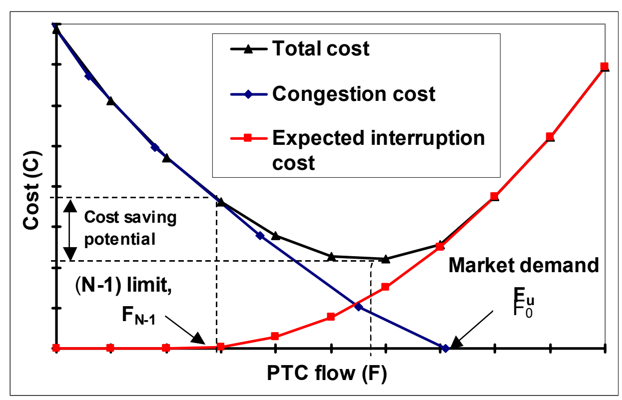

Figure 2 PTC flow limit determined from minimization of total grid operating costs.

The computation of congestion cost is relatively straight-forward, while estimating expected interruption costs will require extensive calculations involving many uncertain factors.

As a first step in using the criterion, the expected interruption costs are replaced with an index reflecting the violations of thermal capacity and voltage limits in the system as a measure of the overall system risk. A closer description of the risk index is given in Section 4.3.

3. SYSTEM OPERATION AND SECURITY ASSESSMENT

The main objective of Statnett SF for using methods for probabilistic security assessment is to increase the capacity in the main grid by:

- Increasing the loading of the existing grid components
- Allowing increased risk for short outages at some places, while
- Keeping the potential consequences under control.

This is illustrated in figure 3.

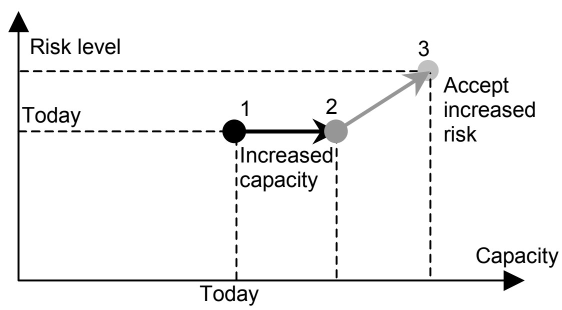

Figure 3 Increasing capacity by accepting increased risk

Increasing the grid capacity from point 1 to point 2 in figure 3, is uncontroversial since the risk level is not changed. Further increasing the capacity to point 3 is accepted if the increased risk is not considered to be unacceptable compared to the benefits related to the rise in grid capacity.

The risk may be addressed in different phases in the stages of system operation.

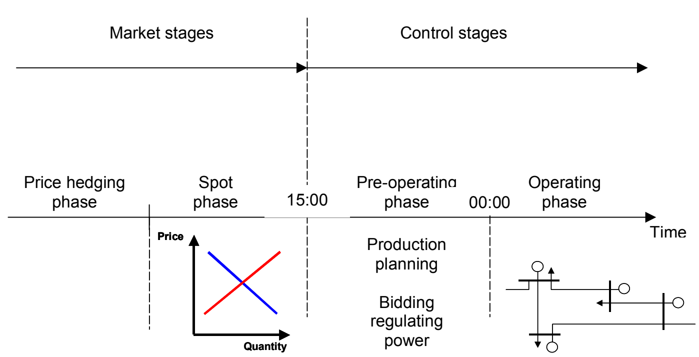

Figure 4 Stages and phases in system operation

The prototype described in this paper addresses the risk management as handled in the spot phase – evaluating the effects of the PTC flow limits with respect to congestion cost between price areas.

4. PROTOTYPE IMPLEMENTATION

The methods for estimation of congestion cost and risk index have been implemented in the computer prototype where the aim has been to test the methods of probabilistic security assessment on real life cases.

The structure of the prototype is illustrated in figure 5.

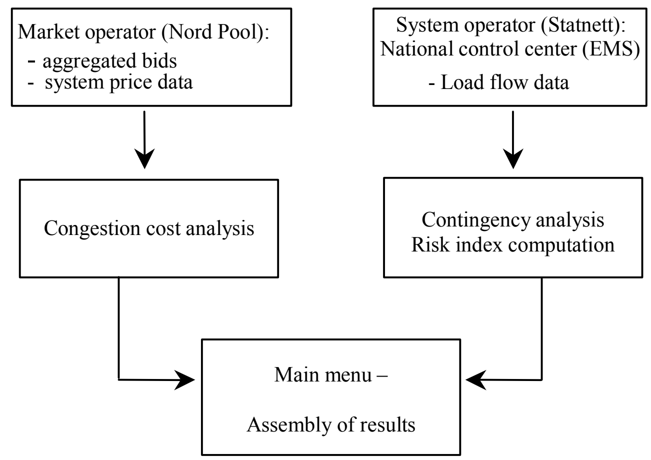

Figure 5 Structure of the prototype

The main menu consists of a graphical interface showing the main areas and power transmission corridors together with the pre-defined PTC limits and flows between price areas in the Nordic power system.

The congestion cost analysis and the computation of risk indices are performed in separate modules. The assembled results of costs and risk indices are presented in the main menu.

4.1 Input data

The congestion cost analysis is performed based on system data from Nord Pool, the Nordic power exchange. The aggregated bid curves for each Elspot area and the system price data is delivered on a predefined format for this use.

For the contingency analysis and computation of risk index a load flow file (PSS/E) being representative for the load flow situation is used. This is established based on the load forecast for the actual hour to be assessed and a best estimate of scheduled generation. The initial load flow file is generated by the EMS system at Statnett's National Control Centre. Based on the initial load flow case, an increase of PTC flow is simulated by increasing generation in the exporting area and decreasing generation in the importing area. Each of the steps in the increasing flow is saved as a new load flow file.

The load flow files are used as input data for the contingency analyses performed [4], and the results from these analyses form the basis for computing the risk index for increasing PTC flow.

4.2 Computation of congestion cost

Congestion costs arise as a consequence when the market demand for power transfer exceeds the flow limit set by the system operator.

In the Norwegian system, bottlenecks are handled in two different ways depending on the operational phase in which the bottleneck occurs, [1]. The price area model is used when congestion is detected prior to the price setting in the Elspot market. This results in a higher price in the receiving end area and a lower price in the sending end area. The other approach is the buy-back model, which is applied when congestion occurs during on-line operation.

The model implemented in this work is the price area model for use in the pre-operating phase (Figure. 4) and for analysis of historical data.

Based on information from the Nordic power exchange, Nord Pool, the congestion costs are being estimated for selected bottlenecks in the transmission system.

An illustration of the computation of congestion costs is shown in figure 6:

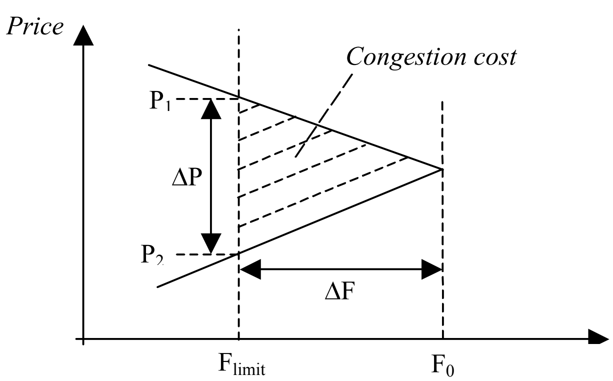

Figure 6 Illustration of congestion costs

In figure 6 ΔP is the price difference between the high (P_1) and low price (P_2), F_0 is the unrestricted PTC flow at system price, and ΔF is the difference between unrestricted (F_0) and actual PTC flow (F_{limit}).

Shown as a function of PTC flow, *F*, the congestion cost has a shape as illustrated in figure 7 – where the cost decreases towards the unrestricted flow, F_0.

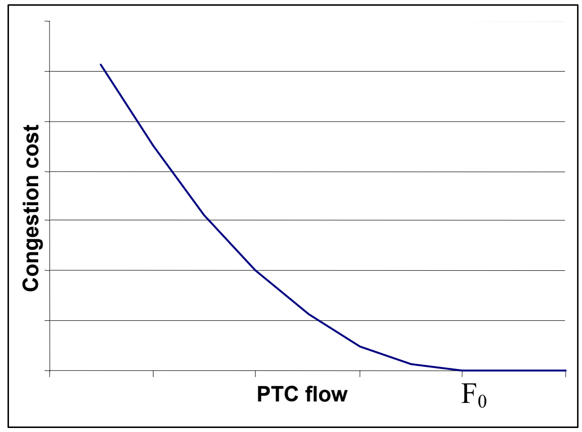

Figure 7 Congestion cost as function of PTC flow

In the prototype the congestion cost is computed by numeric integration of the area between the price curves of the surplus and deficit areas. The price curves are established from Nord Pool system data.

4.3 Computation of risk index / interruption costs

To obtain a measure for the power system risk during operation, computation methods for a risk index has been established. The calculated risk index reflects weighted load and voltage deviations in the system, and shows how increased power transfer between different areas affects system security.

In [1] a method was described to compute expected interruption costs based on contingency analyses and other statistical and empirical information.

Expected interruption costs, C_{EIC}, can generally be expressed as:

$$C_{EIC} = \frac{1}{8760} \sum_{i=1}^{n} \left[\lambda_i(w) \cdot \sum_{j=1}^{m(i)} (p_{ij}(F) \cdot P_{ij} \cdot c_{ij} \cdot r_{ij}) \right] \quad (1)$$

here

λ_i(w)	[failure/year] is the weather dependent annual failure rate associated with contingency *i*.
$p_{ij}(F)$	is the probability of interruption scenario *j* following contingency *i*.
P_{ij}	[MW] is the average power interrupted in scenario *j*.

c_{ij}	[NOK/MWh] is the average specific customer interruption cost in scenario *j*.
r_{ij}	[h] is the average time to restoration of supply in scenario *j*.

To evaluate the risk related to operating the system, a risk index has been defined. This index is calculated based on results from contingency analyses.

The main principle is that the contingencies being evaluated are weighted with the probability of occurrence, and that the consequences of a contingency are quantified using violations of operating limits (branch loads and voltages) during the contingency.

It must be stressed that the risk index can not be used in a cost minimization in the same way as the expected interruption cost can, but it will give the operator useful information concerning risk and operating limit violations as function of the PTC flow.

To compute the risk index the following function has been used:

$$I_{risk} = \frac{1}{8760}\sum_{i=1}^{n}\lambda_i(w)\cdot\left[\sum_j K_{Pj}\left(\frac{\Delta P_j}{P_N}\right)^2 + \sum_j K_{Uj}\left(\frac{\Delta U_j}{U_N}\right)^2\right] \quad (2)$$

where

i	contingency i
λ_i(w)	[failure/year] is the weather dependent annual failure rate associated with contingency i.
j	limit violation j
K_{Pj}	scale factor for weighing of thermal overload
ΔP	overload violation of load limit
P_N	nominal branch load, associated with the thermal capacity of lines and transformers
K_{Uj}	scale factor for weighing of violation of voltage limits
ΔU	violation of voltage limit
U_N	nominal voltage limit

Equation (2) is a quadratic function for weighing violations of load and voltage operation limits.

When applying equation (2) in the prototype a saturation level is implemented for unacceptable operation areas. This has been done to avoid too large contributions from single limit violations, while K_{Pj} and K_{Uj} describe the consequences of such a violation (saturation level).

For voltage violations a saturation function as shown in figure 8 is implemented, while the corresponding function for overloads is shown in figure 9.

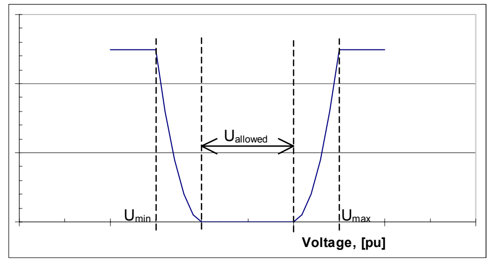

Figure 8 Voltage violation penalty function

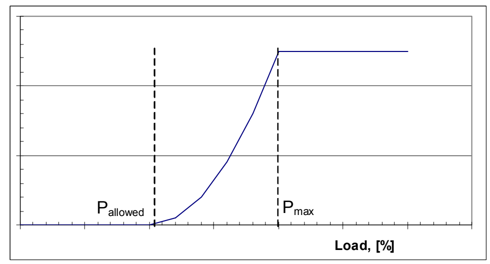

Figure 9 Loading violation penalty function

In the prototype individual scale factors (K_{Pj} and K_{Uj}) can be chosen for different branches, transformers and voltage levels. Thus, it is possible to differentiate the consequences of limit violations, e.g. weighing violations at higher voltage levels more than at lower levels.

5. CASE EXAMPLE

To illustrate the use and the results of the prototype an example case is shown.

The case represents a morning hour in the Nordic power system in the autumn of 2001, and focuses on the Hasle corridor, which is a frequent bottleneck for power transfer between southern Norway (NO1) and Sweden (SE) (see figure 1). In this hour there was a strong demand for power import from Sweden (SE) to Southern Norway (NO1), and the aim of the study is to assess the congestion costs and the operating security level as seen from the Norwegian power system.

This involves the computation of congestion cost and risk index as a function of the allowed power transfer on the PTC.

Figure 10 shows the area prices in Sweden and Southern Norway as functions of the power transfer, and the resulting congestion cost and computed risk index are presented in figure 11.

The unrestricted PTC flow (with no congestion cost) is approximately 2500 MW, while for example the congestion cost for a flow of 1600 MW is 30 000 NOK/hour.

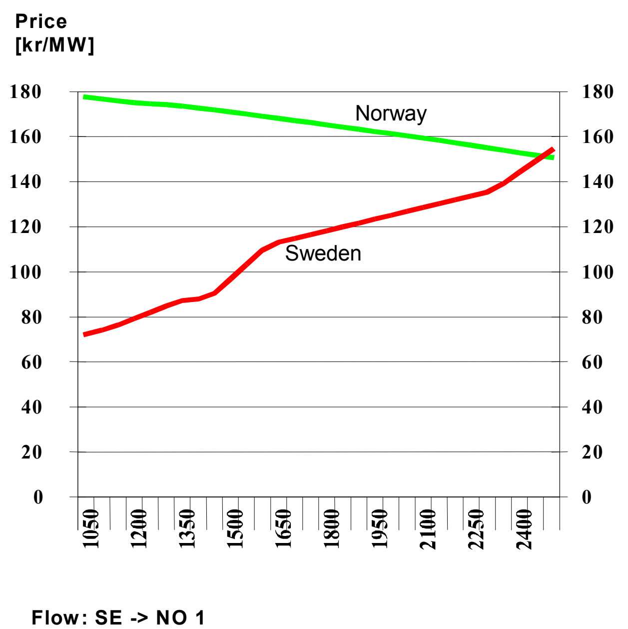

Figure 10 Price curves for the surplus (SE) and deficit area (NO1)

The computed risk index is neglectable up to a PTC flow of 1800 MW. From a PTC flow of approx. 1900 MW the risk index is rapidly increasing with increasing PTC flow, and thus indicating that the transfer limit should be set less than 2000 MW.

The established prototype is currently being tested at Statnett's National control centre, to see whether the information gained from the functions of the prototype will give useful information during operation of the transmission system. The experiences from using the prototype will also give information about possible changes to the computer tool, concerning usability and additional features.

6. CONCLUSIONS AND FURTHER WORK

The established prototype shows a feasible way of computing congestion costs and operational security from system price information and representative load flow files. Based on the results from the computations the system operator can evaluate the consequences of increasing/decreasing PTC limits with respect to both congestion costs and the violations of voltage and branch load limits in the transmission system.

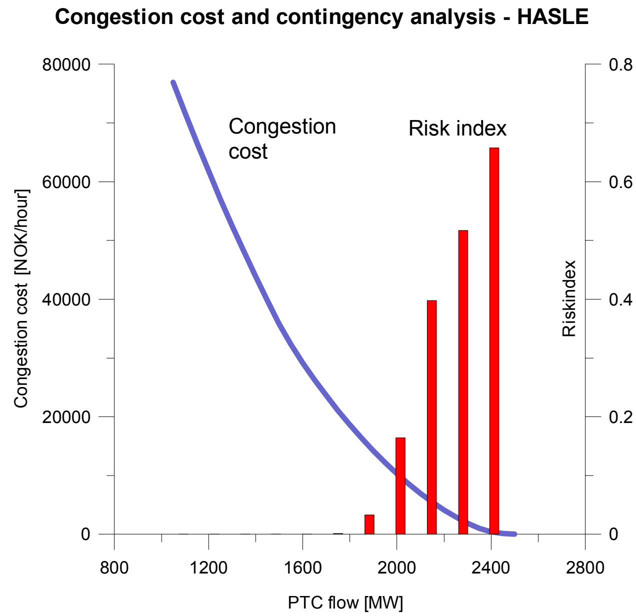

Figure 11 Example: Congestion cost and risk index for the Hasle corridor

In further work the methods of the prototype will be tested to obtain a better basis for evaluating the use of such a tool in day-to-day security assessment as an integrated part of the EMS-system at the National control centre. Additional functionality will be developed to also handle local bottlenecks within an Elspot area. Concurrently, research work is undertaken with the ultimate aim to develop practical methods for computing expected interruption costs in the power transmission system.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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