RESEARCH ARTICLE

Integrated approach for security of electricity supply analysis

Gerd H. Kjølle · Oddbjørn Gjerde

Abstract The methods and tools needed for security of supply assessment range from long term market models for predicting future generation and load patterns to more detailed network simulation models for analyzing contingencies and reliability of supply for delivery points. This paper describes an integrated approach for security of electricity supply analysis, by the integration of power system reliability analysis with the power market analysis. An integrated methodology will enable the long-term security of supply assessment and provide a more consistent input to the various analyses, as well as a better information exchange and interaction between the different methods and tools involved. The integrated methodology is under development in an ongoing research project focusing the power system reliability analysis, making it possible to take the risk of extraordinary events into account.

Keywords Security of supply · Composite system analysis · Integrated approach

1 Introduction

Power system operation as well as the system itself is under change for a number of reasons, typically characterized by uncertainties and risks. Some of the most important driving forces are:

- Uncertainty and delays in power generation and transmission investments
- Higher utilization of the transmission network and stronger variations in power flow together with a more strained power balance
- Integration of considerable amounts of stochastic renewable energy (wind)
- Climate changes imposing increased climatic stress
- Transition to smart energy networks
- Increasing electricity demand and society's dependency to electricity.

In this environment it is a challenge to maintain security of operation and reliability of supply to end customers. System planners and operators need access to adequate analytic and simulation tools that can handle complex models, large amount of information and give clear and transparent decision support. A particular challenge is to include and represent adequately the uncertainties and risks involved. They are caused partly by the stochastic nature of renewable generation such as from hydro and wind and partly by stochastic component failures in the system. Additionally, uncertainties in power markets and prices have rather strong impact on investments in generation and transmission.

Recent studies involving risk of energy shortage as well as risk of wide-area interruptions, have demonstrated the need for a comprehensive and consistent methodology integrating market and network models. One example is the vulnerability analysis of the Nordic power system (Doorman et al. 2004, 2006). This analysis covered risks and vulnerabilities due to energy and capacity shortage and wide spread power system failures. These are all fundamental aspects of the security of electricity supply defined as the ability of an electricity system to supply final customers with electricity

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(Directive 2005). We are facing an international challenge as it has been clearly demonstrated for instance by the blackouts in US/Canada, Italy and Sweden/Denmark in 2003 (Eurelectric 2004) and the one that hit major parts of Europe in November 2006 (UCTE 2007).

The bulk power system is typically dimensioned and operated according to the N-1 criterion, meaning that the system should withstand loss of a single principal component without causing interruptions of supply. The N-1 criterion does neither consider multiple events nor the probabilistic nature of power system failures (Billinton et al. 2008). Contingencies leading to severe consequences will most likely be caused by extraordinary events composed by e.g. two or more failures in the main grid, malfunctioning of the protection system or grid failure while one or more large power plants are on outage. Such multiple events are regarded to have low probability. The traditional reliability analysis based on expectation values is not well suited to capture extraordinary events with low probability and high impact, and there are large challenges related to handling different uncertainties.

The methods and tools needed for security of supply assessment range from long term market models for predicting future generation and load patterns to more detailed network simulation models for analyzing contingencies and reliability of supply for delivery points. The different tools are highly specialized. However, they are fragmented as there are rather weak conceptual and methodological links today, particularly between the power market analysis and the power system reliability assessment. In a power system with a significant portion of stochastic generation such as hydro and wind this is a serious drawback because the set of operational states making the input to the contingency and reliability analysis may not have a sufficiently realistic and adequate base.

This paper presents an integrated approach representing the first step towards providing a comprehensive and consistent methodology for security of supply analysis and risk assessment of power systems. This approach is based on a power market simulator, a power flow model and a methodology for delivery point reliability and interruption cost assessment. The description in this paper emphasizes the power system reliability analysis and provision of necessary input from the power market and contingency analysis.

2 Integration of market and network models

2.1 Framework of integrated methodology

The framework for security of supply analysis and risk assessment of power systems is depicted in Fig. 1 and described in the following.

Power market analysis represents the part where generation and power market scenarios are combined to produce a set of operational states. An *operational state* is defined as a system state valid for a period of time, characterized by load and generation composition including the electrical topological state (breaker positions etc.) and import/export to neighboring areas (Samdal et al. 2006).

The combination of contingency analysis and reliability analysis in Fig. 1 represent the contingency enumeration approach (Samdal et al. 2006; EPRI 1982) for composite generating and transmission system adequacy evaluation. A contingency is here defined as an event composed by outages of one or more components due to failures, which may have technical, human or nature related causes. The contingency enumeration approach comprises three main steps:

(1) Selection and evaluation of contingencies
(2) Consequence analysis of contingencies
(3) Reliability assessment and accumulation of reliability indices.

In Fig. 1 the two-first steps are combined in the Contingency analysis. In the first step of the contingency analysis, the objective is to reduce the number of contingencies for detailed analysis. A typical analysis depth is to include all first and second order independent outages, and dependent outages such as common mode, station originated outages or other user-defined outages. In the consequence analysis of the second step, the objective is to identify which delivery points that will experience interruptions (or reduced supply). This analysis is based on simulations of contingencies in the electric power system using power flow models. The final step is to perform the reliability assessment and accumulate various reliability of supply and interruption cost indices.

Internationally, there are numerous methods and tools dealing with contingency and reliability (adequacy) analysis, see e.g. (Billinton et al. 2001; Allan et al. 1999). Typically, they are starting from a network model with input data from a specific generation and load state for each node in the network. Often, the "worst case"; the heavy (peak) load situation is applied.

In a system where stochastic generation such as hydro and wind is a significant part, selection of operational states for contingency and reliability analysis becomes an important part of the framework. The integrated approach attempts to integrate the power market analysis tools developed to handle stochastic generation and power market issues, with network models handling contingency and reliability analysis. This approach provides a better information exchange and interaction between the different parts of the chain of analyses, thus improving the output generated by the different parts of the framework.

Fig. 1 Framework of integrated methodology for security of supply analysis
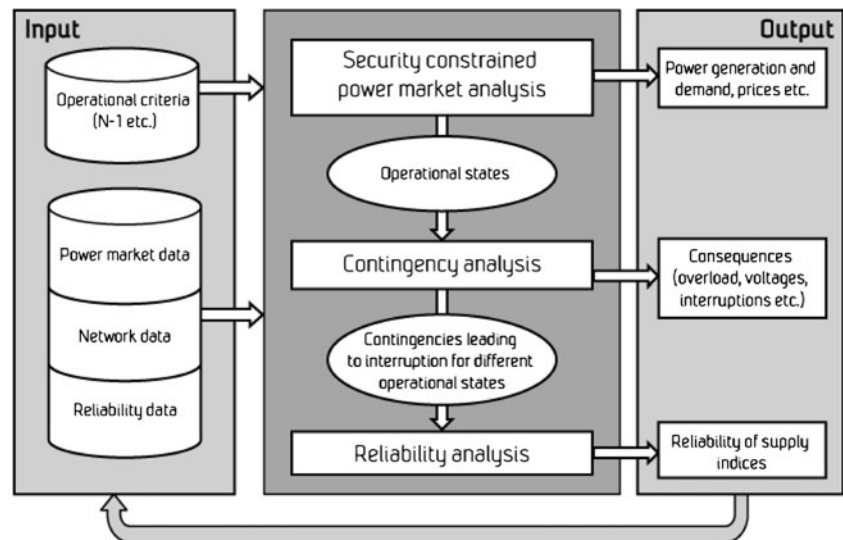
Currently, the framework has been designed, and some of the basic modules have been integrated and tested on realistic sized problems.

The modules utilize three different enabling methodologies or "engines", being a market model, a power flow model and the reliability model. The market and reliability models are described in the following as well as the input and output of the contingency analysis.

2.2 Security constrained power market analysis

The multi-area power market simulator EMPS is a software package for optimization and simulation of hydro thermal power systems (Doorman et al. 2004; Botnen et al. 1992). It is the most commonly applied tool for power market analysis in the Nordic countries today. The EMPS tool calculates the value of stored water for different reservoir fillings, and it simulates the optimal operation of the power system for a sequence of hydrological years. The corresponding equilibrium prices (market clearing or spot prices) affect demand, supply, transmission capacities and the use of water reservoirs. Transmission constraints are included by subdividing the total system in a multi-area model where active power flow is controlled and kept within predefined limits. These transmission capacities are constraints that by definition are exogenous to the market model, and ideally they should reflect thermal limits as well as stability limits. In order to check if the set of generation and demand states generated by the power market model satisfies the transmission constraints a DC power flow analysis is included (Mo 2010). This represents an expansion and enhancement of EMPS, and is referred to as the EMPS with network constraints (EMPS-NC).

By this approach the power market model will generate operational states as input to the next step of the analysis,

such that active power flow is physically modeled and kept within network constraints. Additionally, the method allows for inclusion of deterministic reliability constraints, such as N-1 (as indicated in Fig. 1).

2.3 Contingency analysis and operational states

The objective of the contingency analysis is to identify which delivery points that will experience interruptions (or reduced supply) for any given contingency. The contingency analysis should be carried out for each of the selected operational states to be included in the reliability analysis.

When analyzing the power system e.g. for long term planning one would ideally carry out the analyses for all possible operational states. Utilizing the EMPS model this would for instance mean a total of 75 available hydrological series * 52 weeks * 7 price sections per week = 27,300 different operational states implying corresponding topological states as well as transmission capacities between areas. With e.g. 100 different contingencies to be tested this would require 2.7 million consequence analyses and extensive calculation efforts especially for large systems. In practice the number of operational states will have to be limited. For instance the total number of states can be grouped in 8,760 representative states per year or even limited to a few cases which e.g. can be taken to be representative for one or several months.

The operational states delivered from the security constrained power market analysis do not include information about reactive power due to the use of DC power flow. Therefore, it is a challenge to find stable base case AC power flow operational states including reactive power, from which contingency analysis can be developed. For

this purpose the continuation power flow may be used, in combination with optimal power flow and/or a rule based approach for determining a reasonable voltage profile. This conversion is depicted in Fig. 2. The main idea is to combine active power injections ($\underline{P}_1$) from the security constrained power market analysis (DC power flow results) with a known feasible AC solution providing both apparent power and voltage ($\underline{S}_0$, $\underline{V}_0$), and move in small steps to a new AC solution ($\underline{S}_1$, $\underline{V}_1$) complying with the active power injections ($\underline{P}_1$).

The process of converting the output from the security constrained power market analysis provides a set of operational states suitable as input to the contingency analysis: generation and load for each node in the network model, subdivided in time periods defined in the EMPS model, and supplemented by electrical topological state as shown in Fig. 2.

An important part of the contingency analysis is to assess the consequence of each contingency, taking into account system problems (e.g. overload and voltage problems) as well as possible corrective actions. The analysis can be performed using steady state power flow and/or through dynamic simulations.

Full AC power flow analysis for all possible contingencies, single or multiple, requires extensive calculation effort and time. This is mainly because a large number of power flow cases must be solved as illustrated above. An alternative is therefore to utilize screening techniques to obtain a list of contingencies that possibly will lead to system problems. By solving the first iteration of a Fast Decoupled Load Flow (FDLF) (Stott and Alsac 1974), see Fig. 2, a good estimate for active power flow and an indication of any voltage problem is obtained. The number of power flow cases where detailed analyses need to be carried out, is thereby reduced significantly.
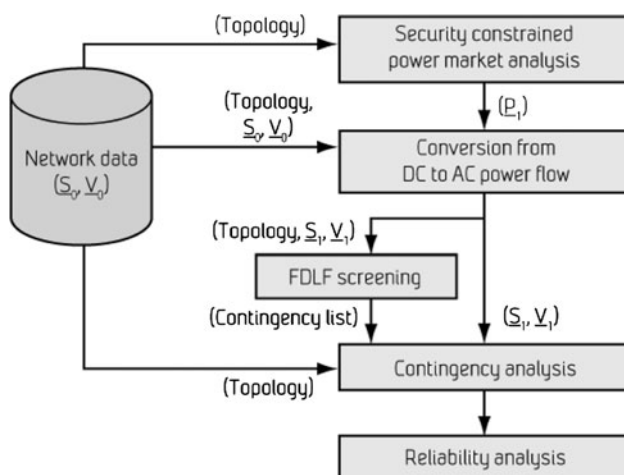
Fig. 2 From market model results to power flow (contingency analysis) input data

The contingency analysis yields as a result a list of contingencies leading to interruption or reduced supply for each of the investigated delivery points. This information is further input to the reliability analysis.

2.4 Reliability analysis and accumulation of reliability indices

In the reliability analysis the objective is to determine the reliability of supply indices for the delivery points under study, i.e. to estimate the frequency and duration of interruptions (or reduced supply), energy not supplied and the corresponding cost of energy not supply (CENS) e.g. according to the Norwegian quality of supply regulation (Langset et al. 2001). For this purpose the OPAL methodology is used (Samdal et al. 2006). OPAL considers interruptions due to primary faults on the power system components as well as protection system faults leading to missing or unwanted breaker operation. The input to the reliability analysis consists of information about which delivery points will experience interruptions or reduced supply.

The methodology takes the critical contingencies (outage events) for a delivery point as a starting point. These contingencies are described as a minimal cut-set structure, including those contingencies found to cause problems through the contingency analysis. The reliability model is based on summation of contributions from the critical contingencies (min. cut-sets). The model is described in (Samdal et al. 2006; Kjølle and Holen 1998) and illustrated in Fig. 3.

A cut-set may represent a single component failure or a multiple independent or dependent event as described above. Each cut-set is represented by an equivalent failure rate (λ_j), outage time (r_j) and the available capacity (SAC_j) to supply the load (P) after the occurrence of contingency j. An interruption occurs for a delivery point when the total capacity is unable to match the load, i.e., when $P > SAC + LG$.

The critical contingencies (cut sets) are deduced for each operational state. Then the reliability indices are calculated per minimal cut for each operational state and each delivery point with fault rates, outage times and specific interruption costs as input.

2.5 Main interfaces

The different modules of the methodology are integrated through interfaces for data exchange between them. The modular structure makes the definition of interfaces quite simple. The two main interfaces are shown in Fig. 1 above and described in the following.

Fig. 3 Reliability model for a general delivery point where P = load in the delivery point (DP), LG = local generation at DP, λ_j = equivalent failure rate for contingency (outage event) j, r_j = equivalent outage time for contingency j, SAC_j = available capacity to supply the load after the occurrence of contingency j
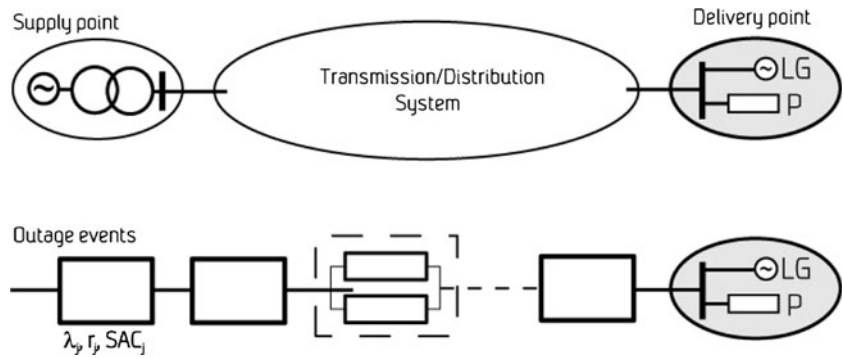
2.5.1 Main interface between power market and contingency analysis

The main output from the security constrained power market analysis and input to the contingency analysis is different discrete operational states, i.e. the compositions of generation and loads. These data are exported from the security constrained power market analysis loop to the contingency and reliability analysis. The operational states must be in compliance with the format required by the power flow "engine" used in the contingency analysis and combined with information about the electrical topological state.

2.5.2 Main interface between contingency analysis and reliability analysis

Main outputs from the contingency analysis and input to the reliability analysis are lists of contingencies leading to interruption for each delivery point and for each of the different discrete operational states with the corresponding system available capacity (SAC).

3 Case study

As an example the integrated methodology is used for a realistic case. The reliability of supply is analyzed for two different delivery points in the 420 kV Norwegian transmission grid. One is situated more or less in the centre of the grid (L1), the other at the end of a line with single sided supply (L2), both in area "10" in the EMPS model shown in Fig. 4 below.

The system was analyzed using three different operational states to represent the year; these were the weeks 4, 16 and 30. Week 4 represents a heavy load situation, week 16 represents a still quite heavy load situation and hydro reservoirs running out of water, while week 30 represents light load. Power flow and market models for year 2010 have been used as a basis with 650 MW load in L1 and 220 MW load in L2.
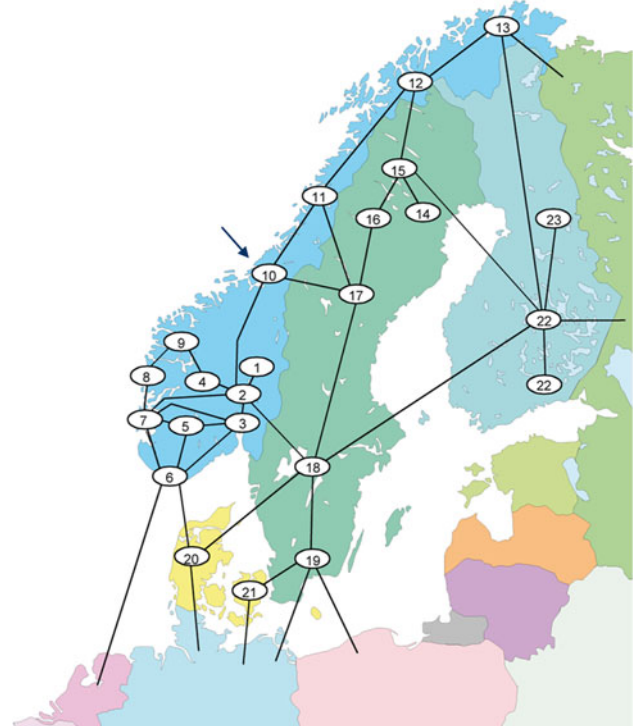

Fig. 4 The EMPS model and division of areas

The first analysis step was to initialize the three operational states through interaction between EMPS (market model) and PSS[TM]E (power flow model) in a security constrained market analysis. In the estimation of transmission capacities to the neighboring areas, the limiting factor turned out to be voltage stability. The EMPS model was updated with the transmission capacities in the different operational states, and their probabilities to occur were provided as input to the contingency analysis.

In this case PSS[TM]TPLAN was used to screen the system and provide a list of contingencies of single outages to be evaluated. Contingencies of double outages were defined manually. A total of 330 single and 46 double outages were analyzed. For each of the 376 contingencies the system consequence was found. This implied to decide whether or not the contingency would lead to an

Fig. 5 Reliability of supply for L1 and L2, compared with the interruption statistics for the period 1996–2005 for delivery points in the Norwegian main grid
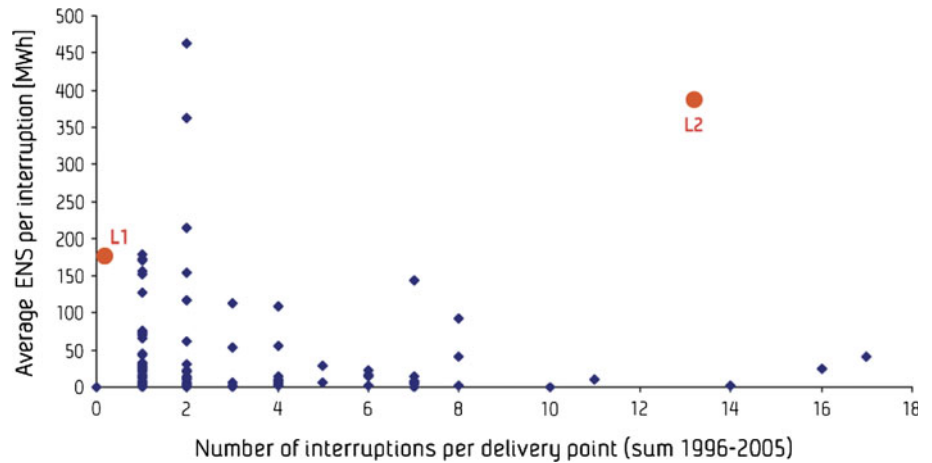
Table 1 Reliability of supply indices for the 420 kV delivery points

Delivery point	No. of interruptions per year	Annual interruption duration (h/year)	Energy not supplied (MWh/year)	Cost of energy not supplied (€/year) (approx.)
L1 (650 MW)	0.03	0.007	4.55	8000
L2 (220 MW)	1.35	2.36	519	3 million

interruption for the load points of interest. Voltages and loads were checked, and it was revealed whether or not the system was within its defined limits. The simulations and consequence analysis led to lists of contingencies which caused interruptions for delivery points L1 and L2 in the different operational states represented by weeks 4, 16 and 30. The interruptions were due to islanding, overload or voltage deviations.

The last step was the reliability of supply assessment. A number of 4–6 critical contingencies (minimal cuts) were identified both for L1 and L2, depending on the operational state. Only first and second order cuts (i.e. single and double outages) were taken into account. Inputs to the reliability analysis were information about the protection configuration, fault statistics and specific interruption costs. For each delivery point and operational state the interruption frequency and duration was calculated by summing up the contributions from the different minimal cuts. To obtain annual indices the indices were then weighted according to the probability of the different operational states. The results for the two delivery points are listed in Table 1, while Fig. 5 gives a comparison with the other delivery points in the main grid.

This example shows that the expected number of interruptions is much higher for delivery point L2 compared with L1. This is as expected because L2 has single sided supply and the single outages are decisive for the reliability of supply indices. The mean time between interruptions is more than 30 years for L1, while L2 will experience an interruption more than once per year on

average, resulting in an interruption cost of about 3 million euro per year. For L1 only double outages contribute. Note that these are dependent outages, arising from the dependencies related to the protection system and missing and unwanted operation of the breakers. The contributions from double independent outages are negligible in this example.

Figure 5 show that L1 has much lower frequency of interruptions than most of the delivery points in the main grid. L2 is one of the points with highest frequency of interruptions and at the same time one of the highest consequences in terms of energy not supplied (and cost) per interruption. Cost-effective measures should be taken to improve the reliability for this delivery point.

4 Conclusions and further work

This paper has presented an on-going work to develop a methodology incorporating power market analysis via power flow and contingency analysis to delivery point reliability analysis. The concept and methodology is demonstrated for a real case in the assessment of reliability of supply and interruption costs for two delivery points in the Norwegian main grid.

The integrated approach presented in this paper is a first step towards providing a consistent methodology for security of supply analysis and risk assessment of power systems. This integration will enable a better information exchange and interaction between the different parts of the chain of analyses, thus improving both the market

simulations and the reliability analysis. This is essential as the power system in many regions is operated with very small margins, and the optimal measures to avoid violations of constraints are often difficult to reveal.

The demand for an integrated methodology capable of addressing technical, economic and societal impacts, is expected to increase due to challenges related to higher utilization of the transmission network and a more strained power balance, stronger variations in power flow, uncertainty in investments, integration of renewable energy such as large wind parks, as well as increased focus on security of supply and vulnerability issues.

The description in this paper has emphasized the reliability analysis and provision of input in terms of operational states to the contingency analysis and available capacity to supply the load after the occurrence of the critical contingencies. The interface between the power market model and the contingency analysis will be further developed, including clustering and screening techniques to handle the large number of operational states originating from the stochastic generation.

One major challenge in risk and vulnerability analysis is to identify extraordinary or inconceivable incidents with the potential of leading to blackouts (wide-area interruptions). The traditional reliability analysis based on expectation values is not well suited to capture such extraordinary events with low probability and high impact, and there are large challenges related to handling different uncertainties. These topics will be further dealt with in the ongoing project.

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