New trends for the assessment of power system security under uncertainty

S. Henry, J. Pompée, L. Devatine, M. Bulot and K. Bell

***Abstract*--A background of increasing uncertainties in all time horizons of power system planning and operation has prompted the development of a comprehensive methodology and an advanced new practical tool for assessing both the static and dynamic security of a real network facing a large number of uncertainties. This paper briefly describes the methodology and then focuses on a study carried out during year 2003, leading to determine total transfer capacities on some French borders.**

***Index Terms*--power system security, uncertainty, data mining, dynamic simulation, operational planning, long-term planning, transfer capacities**

I. Introduction

THIS article deals with statistical studies on the assessment of the static and dynamic security of a real network facing a large set of uncertainties. In RTE, a first complete study has been carried out with statistical methods during the year 1998. It concerned the determination of operating rules against voltage collapse in the South-East part of the French network [1]. The new rules allowed the economy of 1 M€ each year. These results were considered as very interesting, and therefore, we have continuously developed the statistical and probabilistic methods and tools [2].

In NGT, since 1990 the development of the transmission system in terms of its secure capacity has been subject to uncertainties imposed by the commercial separation of generation from transmission meaning that the transmission owner cannot know the dates and locations of openings and closures of power stations. This has encouraged in interest in probabilistic methods to manage the risks, in particular those associated with possible insufficiency of system capacity [3].

The techniques hitherto explored by RTE and NGT have a lot in common and led to collaboration, started in 1999, in which a comprehensive methodology could be better defined and a powerful and flexible tool developed allowing its application. This has led to the implementation of 'ASSESS' software [4]. Therefore, after a short presentation of the methodology, this paper will mainly describe a study carried out during year 2003 as well as outlining other studies that are ongoing. The presented study allows the determination of total transfer capacities on some French borders, playing on the level of load and pattern of generation in France and neighbour countries.

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II. The Methodology

A. Context and objectives

With the growth of uncertainties (on prices, on localisation of production…), the assessment of power system security is an increasingly complex problem. Moreover, in the context of more market-oriented industries, system security limits are seen as constraints preventing the market from being operated according only to economic rules. Therefore, it is now necessary to analyse a sufficiently large number of scenarios in order to take into account the uncertainties, assess security level with sufficient confidence and devise robust and understandable results. The methodology is mainly designed to be used:

- In the context of **system planning** (i.e. investment and reinforcement planning), alternative system configurations must be screened for a lot of generation and load patterns and a large number of contingencies in order that investments can be well targeted and risks quantified.
- In the context of **operation planning** (i.e. maintenance scheduling, design of operating strategies, protection settings, etc.) security assessment is needed to make better use of available resources and to reduce system operational costs without compromising the security of supply and the integrity of equipment.

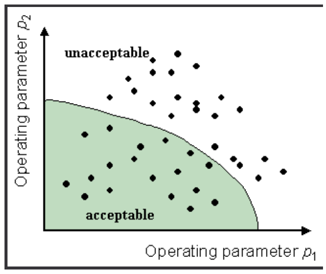

Fig. 1. Concept overview

Conceptually, the objective of the 'ASSESS' methodology is as in figure 1. Numerous situations are built, classified as admissible or non-admissible, and then analysed to find the operating parameters (voltages, flows…) which best characterise the boundary between admissible and non-admissible. The methodology also allows the characterisation of a set of situations regarding their security level, their weak points, the way the security might not be assumed (voltage collapse, overflows…).

B. Main steps of the methodology

The 4 main steps of the methodology (figure 2) are described in the following sections.

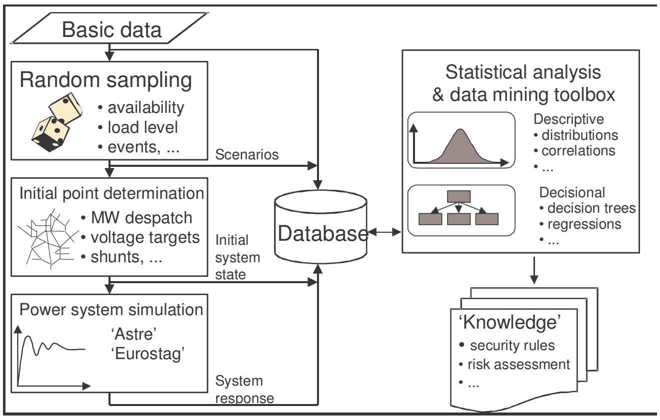

Fig 2. Methodology overview

1) Random sampling

All the technical and economical data that characterise the static state of the system, and all the technical data that characterise the system dynamic behaviour can potentially be sampled, for example:

- generation capacity, localisation and prices: This allows the sampling of wind power unit localisation and production with the use of laws modelling wind strength in the different areas of the network;
- load localisation and level: It is possible to sample, on a set of nodes, the total load value and, if needed, the distribution among the nodes and the load power factor;
- depth and localisation of line and plant unavailabilities (planned maintenance, previous faults): The user can limit the number of ('planned') unavailabilities to some maximum, and to make unavailabilities dependent on the in-service states of other devices so as to ensure that a modelled planned outage pattern is realistic;
- parameter values of automata (such as protections, load-shedding systems, tap changers, etc);
- the sequences of events that can occur on the network (such as onset and clearance time of transient faults, the timing of switching actions, etc).

Note that some laws can be used to carry out parametric studies. For statistically valid outcomes, experience suggests that around 5000-15000 variants or scenarios should be computed.

2) Determination of a realistic initial working point and assessment of its static security

Each sampled variant can be quite different from the base case. Its initial working point must be determined so as to represent a feasible situation such as might be prepared by the operational planners and implemented by operators. This means that the generation start-up and dispatch, the voltage set-points, the switch statuses of shunt compensation, the taps on manually-tapped transformers and phase shifters and the Mvar generation must be realistic. Further,

- the MW dispatch must realistically reflect generators' likely or sampled market positions;
- the initial states must respect the chosen security rules, e.g. 'N-1', 'N-k', etc.;
- control limits must be respected: maximum and minimum active and reactive power, etc.

A security-constrained optimal power flow (SC-OPF) is used to achieve this, named Tropic [5], based on non-linear interior point methods. It performs a fully coupled 'AC' single state optimisation of the 'planned' pre-contingency system with additional 'DC' thermal contingency constraints. In addition, the function includes a module for voltage refinement, able to study N-k security in a full AC model and optimise the voltage variables. The function also gives access to an AC security analysis with contingency ranking using 'Astre' (see below).

If all the constraints of the SC-OPF cannot be achieved, the criteria are relaxed in a consistent manner (mainly by means of load shedding or add of Mvars) so that the initial state remains, to some degree, feasible. In this way, all the computed initial states are suitable for dynamic simulation (where chosen) and allow the study of the static security level by analyse of the found constraints, of the generation and operational costs… Therefore, it is possible to find system-weakened parts, to study new operational rules or reinforcements.

3) Dynamic simulations (optional)

If the outcome of a security-constrained optimisation and its implicit analysis of static security is not by itself sufficient for the purposes of a study, 'Assess' offers a choice of two dynamic tools 'Astre' [6,7] and 'Eurostag' [8]. The user decides which to use depending on the chosen balance between the precision of results, available computation resources and the elementary computation time.

'Astre' is a quasi-steady state simulator and contains a facility allowing the calculation of security margins, i.e. the degree to which the modelled system can be stressed. Regulations, long-term controls and protection devices are modelled simply but directly.

'Eurostag' is a time domain simulation tool which models both fast electro-mechanical dynamics and slow response system controls. It is particularly useful for its versatility in modelling any kind of regulator, and its efficiency, due to the use of a variable computation step size. A very large variety of automaton models is also available that help to model any centralised or local regulation.

4) Statistical analysis

During the study process, all the results are stored in various tables. They include the sampling characteristics, initial point determination and dynamic computation results. The search for the main influences on security is done through the use of several statistical methods implemented in third party tools. Classically, the engineer will first try to have a better understanding of the main parameters by means of filters launched using a graphical user interface and by means of first level statistical analysis (histograms, repartition functions, means, variances and correlations…). Then, to find better characterisation of the results, powerful statistical methods are used such as: Clustering, Principal Component Analysis, Decision Tree [9,10].

In the first instance, depending on the nature of the sampling undertaken, the described approach gives statistical results in which the probability of each scenario is not taken into account. However, it is also possible, when necessary for certain studies, to weight the different situations with respect to their relative probability of occurrence in order for the analysis to give a characterisation of risk [11] .

The **expected results** from the analysis are:

- In the field of planning, the necessity for investment in network reinforcement and the real value obtained from it can be determined;
- In the field of operational planning, robust exploitation rules can be designed for assessing security.

III. Application: Determination of total transfer capacities on some French borders

A. Objectives of the study

The determination of total transfer capacities on network borders is a very important problem for the European operators, especially for the French operator, who is in the centre of many electrical commercial roads due to its frontier with Spain, England, Belgium, Luxembourg, Germany, Switzerland and Italy. The scope of our study is to characterise total transfer capacities on some French borders, playing on the level of load and pattern of generation in France and neighbour countries.

Our aim is not to characterise available transfer capacity on a specific network configuration as RTE is doing this each day and therefore the exposed method is not the reference method for day-to-day RTE available transfer capacity computations. In fact, the objective is to obtain a determination of the various constraints limiting the transfer capacities on a wide set of situations modelling some typical operational planning conditions. By now, the method has only been used in order to have a better view of the constraints on various situations.

B. Studied network and sampled situations

In order to have a correct image of the phenomena involved in the determination of transfer capacity, the study is carried out in 2 stages (summer and winter conditions) on a network modelling the entire UCTE transmission network. The studied network is built using snapshots exchanged between the UCTE operators and contains 4 200 nodes (mainly 400 kV and 225 kV), 6 900 lines and transformers and 1 400 generators.

The RTE network is modelled using the real operational limits on line and transformer transits, as well as on node voltages. The representation of all the main French production units with their limitations in terms of PQ diagram is also given. Meanwhile, the foreign networks have a not so realistic model in terms of transit, voltage and production limits as the study of the internal limits, which can be reached on these networks, is out of the scope of the study. Only standard voltage and transit limitations are set on these foreign networks. This important remark means that we will always have an optimistic image of the total transfer capacity of the French interconnection lines because some limits can’t be reached due to constraints on foreign networks, which can actually appear prior to constraints on RTE network.

The preparation of the studied networks is a quite long step but also the most important stage of the study. Here, we need to have correct operational planning schemes in terms of substation configuration. As we want to explore the limitations on maximum transfer capacity, we have to choose the best substation configurations. This is done with the help of the French dispatchers.

Using this network model, we want to obtain a realistic set of situations modelling as best as possible the variations, which can be seen in terms of transit on the interconnection lines, using the following sampling laws:

- Law 1: For the French/United Kingdom interconnection, the sampling is simple as the link is a single DC link. Therefore, we sample only the value of the injection with a uniform law between – 2 000 MW and + 2 000 MW. During the SC-OPF computations, the disequilibrium introduced by the sampling of this injection will be fully compensated by French production units.
- Law 2: For all the other foreign countries, a sampling is carried out on the total load and production level of the considered country. The sampling of load and production is done independently and leads to change the global balance of each country. As for the French/United Kingdom interconnection, the disequilibrium introduced will be fully compensated by French production units.

In order to have different transit patterns on the French interconnection lines, the geographic repartition of foreign total load and production is also sampled according to different areas. Of course, loads are only sampled on consumer nodes and production levels on nodes where units are connected. In this way, we are able to produce situations with a wide variety of local area balance leading to the creation of various transit patterns among the networks. As we are not studying the precise transit and voltage limits on the foreign networks, the sampled situations have not to be fully realistic for these networks as long as the transits observed on French interconnection lines are realistic.

- Law 3: Additionally on the RTE network, where we want to observe security constraints, and where the production/load balance is done thanks to the French production units, we sample variables in order to have various production patterns. To do so, we first sample the availability of the main production units in order to represent the effect of maintenance. With such laws, in the analysis of the winter network, we sample between 0 and 5 unavailable nuclear power plants. The sampling also respects rules giving the maximum number of simultaneous unavailabilities on each specific production site. In this way, we forbid the creation of non-realistic situations.

A second sampling is carried out on the French production units. It concerns their production price, which are sampled around their mean value using a gaussian law. Of course, such a law respects the price orders between hydraulic, nuclear, fuel and gas units but can change the price order between units of the same category. This allows the computation of various production plans by the SC-OPF that will use the cheapest available units for each situation with respect to all the constraints.

For each of the winter and the summer study, 2000 situations are produced using these sampling laws.

C. *Determination of realistic working points and assessment of static security*

The previously described sampling leads to the creation of various unbalanced situations. The SC-OPF is used in order to determine the French production plan using the power plant availability and prices (sampled with law 3). The foreign production plan is not changed by this computation as we have fixed it during the sampling of the balance of each foreign country (with law 2). The start-up plan is chosen with respect of the operational N-1 rule in RTE. In case of impossibility to respect the constraints, the SC-OPF will shed the minimum level of load necessary in order to solve the transit problems.

For each studied situation, we obtain the following main results:

- production plan with the active and reactive production level of each power plant;
- voltage at each node;
- transit and percentage of load of each branch;
- some global results as the balance on each country, the production of each power plant owner, the production prices (by country, by owner)…
- reached constraints that forbid to use cheaper production units or that forbid to have greater exchanges between countries. This is the most important result for our study. Here, for each simulated N-1 contingency, we obtain the constrained branches with for each one the strength of the constraint. If the constraints have been solved using load-shedding, we also have the amount and localisation of this load-shedding.

Note that 2% of the computations do not converge with the SC-OPF. They mainly correspond to samplings that are unrealistic.

D. *Statistical analysis*

The first step of the analysis is done using some very simple tools such as the observation of some variables using means, variance and some graphics.

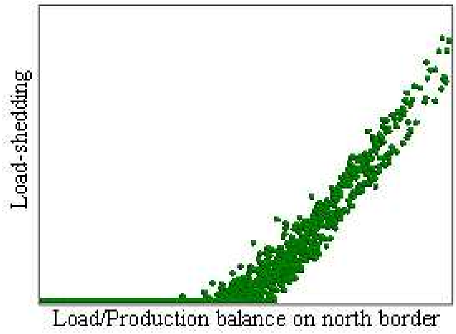

Fig. 3. Balance and load-shedding on north border

Figure 3 shows the scenario relationship between the exchange on the northern border and load-shedding to achieve security within France. In the result database, we obtain 35 % of situations with 0 MW of load-shedding. For the situations with no load-shedding, the corresponding exchanges between France and its neighbours are possible and correspond exactly to the sampled values. For the situations, where the amount of load-shedding is positive, there is at least one constraint, which prevents us from going to greater exchange levels. In general, when there is load shedding, the border exchanges from the converged SC-OPF are different from those originally sampled. The analysis of these situations gives us precisions on the reached constraint and on the specific patterns leading to these constraints.

For each constrained situation, we have the contingency for which the constraint is active, the constrained branches and for each one the level of the constraint. Thanks to the load-shedding, the corresponding situation will have no violated constraints but only quasi-reached constraints (i.e.: the flows are at their maximum limit either in N or in N-k). Therefore, with these situations, we have a value of the maximum exchange level.

During this first stage of the analysis, we have checked that the produced situations were comparable to the ones observed in real time. This important result proves us that the methodology is correct in order to build realistic network situations. Meanwhile, we will see after that we were not able to produce situations with enough diversity in terms of production plan.

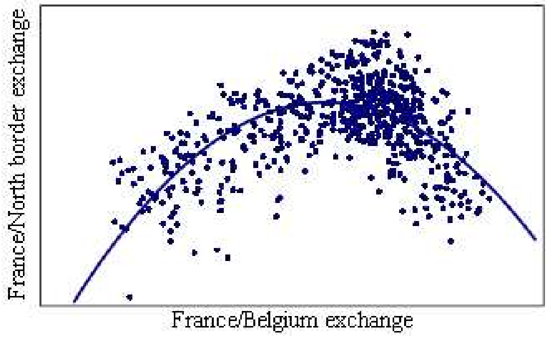

Fig. 4. North border maximum exchanges

Figure 4 shows only the constrained situations on the north border. Here, we have situations at the maximum level of exchange on these borders taking into account the found constraints. Of course, we can observe that the theoretical maximum transit is never reached. This maximum transit level corresponds to the sum of the line capacities. But before reaching it, we always activate a constraint, which depends on the production plan in France and the balance on foreign networks and therefore on the influence coefficients that describe the loop flows (whose values can be determined).

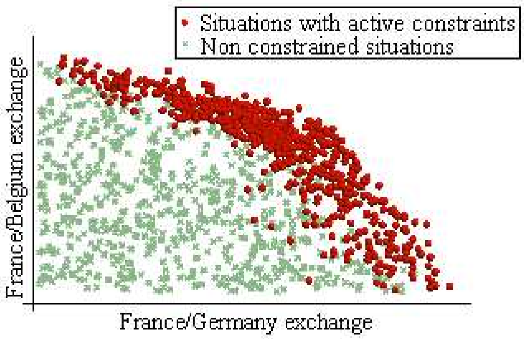

Fig. 5. North border exchanges

Figure 5 shows all the situations in regard of the exchange on the French/Belgium and French/Germany borders. The darker points are the constrained situations, and we can see that they almost all correspond to the maximum exchange levels. For these constrained situations, on the left hand side, we find the situations with active constraints near the Belgium interconnection lines, on the right hand side, the ones with constraints near the German interconnections and in the middle the situations with both constraints. Then, using only the constrained situations, we can seek the maximum exchange levels on the north border with the influence of one parameter (figure 4). Such an analysis is carried out on each border and allows the determination of the maximum transfer capacities and of the constraints causing the transfer limit.

A second step is carried out in the analysis in order to find the global patterns leading to more or fewer constraints and therefore more or less total transfer capacity. This analysis uses regressions and decision trees. For example, we can try to find the relationship between the transits on French/Belgium interconnection lines and the production of the French power plants, the level of the French/English exchange, etc. In such an analysis, using a linear regression, we have found a relationship of the kind:

Belgium transit = x1.Belgium exchange + x2.German exchange + x3.England exchange + x4.Nuclear site A production + x5. Nuclear site B production

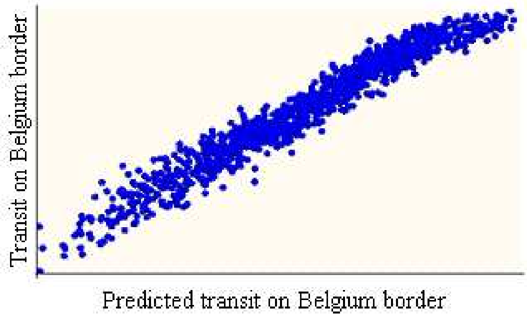

Fig. 6. Estimation of the prediction model

The obtained model proves to be quite a good predictor of the available transfer capacity (figure 6). However, using this method, we have only obtained partial characterisation with a limited influence of the French power plant production levels. The reason is that we have insufficient production plan diversity on the constrained situations. Indeed, we have sampled the availability and production price of the units but we have not fixed by sampling different values for the main unit production. Therefore, to solve constraints, the SC-OPF had always the possibility to use the available units even if their price is high (they are still cheaper than shedding load) and the production plan is always modified in order to have the greater possible exchanges.

E. Conclusions

This study gave us a better knowledge of the limitations of the total transfer capacity on French interconnections. The most interesting fact is that we have obtained a good view of the situations, which may occur all year long. Still in the scope of transfer capacity, the method is very interesting for the study of reinforcements of the network. For each possible technical solution (change of line conductors, change in substation…), we can carry out similar computations and therefore compare the different efficiencies. However, the method is quite heavy with long preparation and study time as well as a need for a high level of expertise from the responsible engineers.

Moreover, some improvements of this study methodology could be tested in order to be able to refine the obtained results. As we have seen in the previous section, the first improvement consists in sampling the level of production of some of the main French generators. This will lead to the creation of more various French production plans and will allow the study of the influence of each generator towards the transfer capacity limits. In addition, we could also analyse the effect of the line maintenance and of the variation of the French load, which was fixed in the former study.

IV. Future perspectives

The scope of use of 'Assess' is very wide, from long-term planning to some general study in the operational planning domain. The described method has been used during the last 18 months to carry out 10 different studies either in RTE or in NGT.

The subjects of our main ongoing studies are:

- Study of the wind generation constraint volumes (long-term planning);
- Study of the future French network with the uncertainties on production (wind power localisation and amount, new thermal units) and exchanges with foreign countries (long-term planning);
- Study of the angular stability limit on the Anglo-Scottish interconnector boundary (long-term and operational planning);
- Determination of operating rules against voltage collapse in the South-Est part of the French network (operational planning). This study is a refinement of the studies exposed in the introduction of this paper.
- Study of the influence of a new automaton on the stability (operational planning).

As well providing valuable new information on system conditions and performance that it has not previously been practical to obtain, the experience gained from these first studies allows us to improve our tools and methods and to try them for new types of study.

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