APPLICATION OF A DATA MINING BASED TECHNIQUE FOR THE EVALUATION OF TRANSMISSION EXPANSION PLANS

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Abstract - This paper describes a methodology for the study of long-term network planning under uncertainties. In this approach the major external uncertainties during the planning horizon are modelled as macro-scenarios at different future time instants. The random nature of actual operating conditions is taken into account by using a probabilistic model of micro-scenarios based on past statistics. Monte-Carlo simulations are used to generate and simulate a specified number of scenarios. Data mining techniques are then applied to the simulations results collected in a database, so as to extract information and to rank scenarios and network reinforcements according to different performance criteria. The paper describes the application of this approach on a real transmission planning problem faced by the Belgian transmission system operator.

Keywords - Data Mining, power system planning, probabilistic method, random sampling, Monte-Carlo, real example

1 INTRODUCTION

In Europe, the transmission system operator (TSO) is responsible for operating, maintaining and developing the high voltage grid. The liberalisation of the electric sector means that the transmission system operator should leave maximum freedom to the transactions, while ensuring the system security and providing access to the grid in a non-discriminatory way. At the same time each TSO is asked to minimise his own costs and to justify them in a transparent way.

In this context, transmission system planning tends to become more and more difficult, in particular due to the highly uncertain nature of the environment. Of course, load demand growth and unscheduled exchanges with neighbouring systems are the major sources of uncertainties in transmission system planning. However today, after the un-bundling of electrical companies, the operation of the existing generation plants, the de-commissioning of generation units, and the location of future power plants become more and more blurred. Moreover, because of the heterogeneous characteristics of the various energy markets, due to different economic, political, social and regulatory environments, diverse ways of adapting transmission planning functions should be considered. Successful transmission planning functions should handle as main uncertainties the size and the location of new power plants, the de-commissioning of existing power plants, the growth of customer demand, the growth of embedded generation, the evolution of transit flows and the amount of power imported/exported.

Several approaches have already been proposed and implemented [1]. Those approaches can be classified as deterministic and probabilistic [2, 3, 4]. Deterministic approaches analyse, on a case-by-case basis, a certain number of reference scenarios by simulating them and evaluating security criteria. Probabilistic approaches generalise this principle by analysing (either explicitly or implicitly) a much larger number of scenarios and by taking into account their probability of occurrence [5].

The approach described in this paper is part of a general effort made by the Belgian TSO to improve methodologies so as to cope in a more efficient way with the expansion planning process. It has been developed within a research collaboration between ELIA (Belgian TSO) and the University of Liège. It should be considered both deterministic and probabilistic. Indeed, on the first hand, the major external uncertainties during the planning horizon are modelled as an enumeration of envisaged macro-scenarios, i.e. combinations of high-level hypotheses, at different future time instants. On the other hand, the random nature of actual operating conditions is taken into account by sampling a probabilistic model generating micro-scenarios induced from past statistics. Monte-Carlo simulations are used to generate a database of system evolution scenarios. Data mining techniques are then applied to analyse the results and to evaluate the planning options. The resulting methodology and software tools were first presented in [7]; the present paper focuses on their application to a real transmission planning problem faced by the Belgian TSO, with the objective of determining the efficiency in terms of security margins with respect to the different high-level hypotheses of transmission network reinforcements on the South border of the Belgian system.

The rest of the paper is organised as follows. Section 2 describes the main steps of the approach, whereas Section

3 focuses on the particular study carried out on the Belgian grid. Section 4 provides conclusions and main future directions of work.

2 APPROACH

2.1 The problem

Every considered network expansion option should be evaluated under the point of view of security, flexibility, and robustness. Our methodology compares network reinforcement solutions regarding the compromise between security and costs through different system evolutions. Therefore those solutions should be evaluated in a several years planning horizon taking into account the uncertainties related to this period. The selection criteria are based on levels of flexibility and robustness of the development options. The robustness represents the capability of a development option to face the system evolution, while the flexibility gives a measure of its capability to be re-oriented after a given amount of time, according to the actual system evolution.

2.2 General principle

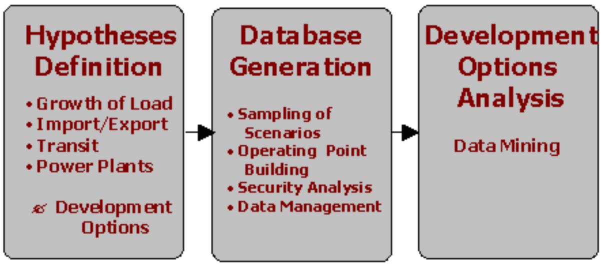

Figure 1: The different steps

Figure 1 shows the different steps of the methodology. First several hypotheses are chosen by experts in order to define the range of the study in terms of macro-scenarios, planning options and contingency lists; the specification of sampling distributions is obtained from past statistics. The database is then populated automatically using Monte-Carlo sampling and numerical simulations. Finally, the results are analysed using data mining techniques in order to evaluate and compare the development options.

2.2.1 Hypotheses Definition

In our nomenclature, a *reinforcement* is defined as an installation or change of a particular network equipment and a *development option* as a collection of reinforcements taken at particular time instants during the planning horizon. Figure 2 illustrates a case where the planning horizon is seven years and where one macro-scenario is considered at t_0, two macro-scenarios at time t_{0+2}, and three at time t_{0+7}. Every development option is assessed according to those different hypotheses. A power system state at a given time is called *micro-scenario*. A *macro-scenario* consists in a set of micro-scenarios corresponding to a hypothesis of parameters uncontrolled by the planner (e.g. peak load, import and transit at a given time). A temporal sequence of macro-scenarios corresponding to a possible network temporal evolution is called a *trajectory*.

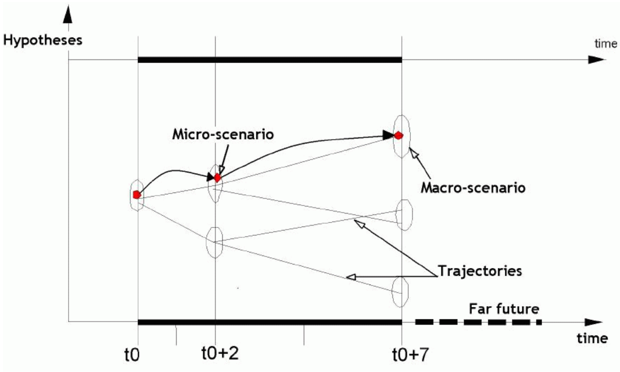

Figure 2: Hypotheses space

From an a priori defined set of possible reinforcements, a set of candidate development options is constructed, specifying which reinforcements are combined and at which time instant they apply. At each time step of the planning horizon, a set of macro-scenarios is specified. These macro-scenarios represent combinations of assumptions concerning the main sources of uncertainties, which are not under the control of the planner, such as future load demand growth, import, transit, size and location of new power plants. Note that each macro-scenario consists in a virtually infinite set of possible operating conditions, the so called micro-scenarios, corresponding to the predefined assumptions combined with random variations of network topology to simulate somehow the maintenance, load demand and generation pattern. The micro-scenarios are automatically generated by Monte-Carlo simulations, based on past statistics and on the macro-scenario specification. The hypotheses are based on a priori information such as system knowledge (possibly interesting reinforcements determined by the deterministic planning) and medium and long-term forecasts (plausible macro-scenario specifications).

2.2.2 Database generation

In order to carry out differential analyses among macro-scenarios, *reference micro-scenarios* have been used in such a way that the variance on different observed indices is mainly due to the high-level hypotheses. For every macro-scenario, each simulated micro-scenario is then related to a reference micro-scenario. Each reference micro-scenario is randomly determined by selecting online network equipments and generators and by generating a load pattern defining how the load is distributed among individual buses and types of consumers. This random sampling is driven by a probabilistic model based on past statistics. The number of reference micro-scenarios needs to be sufficiently large (at least a few hundred samples) to be statistically representative of the possible system operating points.

Once the reference scenarios have been generated, the micro-scenarios corresponding to each macro-scenario are computed. The generating units are dispatched according to a classical economic dispatch[1]. Then an optimal power flow software (OPF) is used to compute a realistic and feasible initial operating point, in terms of Mvar scheduling (see [7] for more details about the OPF application). The static security of the obtained network state is evaluated for a predefined set of contingencies. The results are filtered, stored and converted in synthetic security indices. Notice that, during the analysis phase, these security indices will be aggregated in the form of an overall security level of each micro-scenario, and, at higher level, of each macro-scenario and each trajectory.

2.2.3 *Analysis of results using data mining*

The methodology may produce very large amounts of data. For example, in a study based on a few hundred reference micro-scenarios, about 100 macro-scenarios and a moderate number of reinforcements, this yields a database potentially composed of a very large number of simulation results (in the order of several hundred million of security indices), classified in terms of characteristics of macro-scenarios, micro-scenarios, contingencies and reinforcements. The different development options must be analysed according to their robustness and flexibility of achieving their objectives. The constraining scenarios should be identified. These analyses are carried out using a set of data mining tools (data summarisation, graphics, automatic learning techniques) in order to help the power system engineers together with people experienced in data mining to extract from the database synthetic information, related to micro-scenarios, macro-scenarios, trajectories and reinforcements but also particular power equipments.

3 APPLICATION TO THE BELGIAN GRID

The objective of the Belgian TSO was to determine the efficiency in terms of security margins with respect to the different high-level hypotheses of a transmission network reinforcement on his South border. Although this transmission expansion problem is complex our proposed methodology has managed to produce solutions satisfying transmission expansion experts of the Belgian TSO. The analysis phase has shown that data mining techniques can be used in order to properly explain the results, to identify the implied phenomena, to determine the causes and to find out the actual gains of proposed reinforcements.

3.1 *Overview of the Belgian power system*

The main characteristics of the Belgian power system are as follows (2002 data and 2003-provisional data):

- Installed power: 14.9 GW;
- Peak load: 13.6 GW;
- Consumption: 80.4 TWh;
- Imports: 16.7 TWh / Exports: 9 TWh.

The grid consists of overhead lines and underground cables with voltages ranging from 30 kV to 380 kV. The voltage is converted in stages to the required level at more than 800 sub-stations. The high-voltage grid is composed of 8,286 kilometres of connections: 5,607 km of overhead lines and 2,679 km of underground cables. The ELIA network performs three major functions. The 380 kV grid forms the backbone of the Belgian and European network. The 220 and 150 kV connections provide electricity to large consumption centres and ensure Belgium's domestic supply. Finally, power is carried over 70 and 36 kV lines to the off-take points used by distribution companies. Large industrial customers are directly connected to the high-voltage grid. The Belgian network forms an integral part of the European transmission network. Connections with the Netherlands and France primarily carry electricity at 380 kV.

Belgium is strongly embedded into the European grid. Therefore it also has to deal with 'loop flows'. These are uncontrolled energy flows running through the international electricity system. This might be problematic for a small network as the Belgian one, wedged between large electricity producers and consumers. Moreover, these international flows constitute one of the most relevant sources of uncertainties for the near future. Their impact on the system security should therefore be investigated.

3.2 *Reinforcements & high-level hypotheses*

The study has been performed on the 1400-bus network used by ELIA for planning studies. The first objective of the study being described in [7], the focus will concentrate on the reinforcements and the high-level hypotheses taken into account for this study.

The planning horizon was originally fixed to seven years and divided in two periods: from present time t_0 to t_{0+2} and from t_{0+2} to t_{0+7}. Only the first period is considered in the application. Only one 380 kV reinforcement has been taken into account and applied at t_{0+2}. Note that the option of no reinforcement is also considered.

At each time step of the planning horizon, the uncertainties, not under the control of the planner are modelled through macro-scenarios hypotheses. Only one source of uncertainties has been considered in the study: the level of import 1000 MW and 2000 MW at t_{0+2}. The generation pattern changes from t_0 to t_{0+2}: removal of old coal units and addition of a new combined cycle gas-turbine plant. The peak load is 14.08 GW at t_0 and 14.63 GW at t_{0+2}. In the sequel, we will call the different macro-scenario/reinforcement combinations using the following triplet: $[t, I, r]$ where t refers to time-step (t_0 or t_{0+2}), I to the import level (1000 MW or 2000 MW) and r to the reinforcement.

The Monte-Carlo method has been used to generate a set of 997 random variations of system topology, load demand and generation pattern. The system variants are derived from the existing network assuming all equipments

[1] We have used a marginal cost based dispatch. Admittedly, in some systems a more realistic market model, taking into account market clearing mechanisms and the possibility of market power, should be used. Nevertheless, in the context of the present study this simple dispatch scheme was considered as sufficient. Note also that the call to competing producers outside Belgium can be taken into account in the methodology in the form of uncertainties represented by a set of macro-scenarios.

connected. For each scenario, the random sampler sets the unavailable equipments (lines, cables, transformers, shunt capacitors and generating units) and the global load level according to a probabilistic model derived from past statistics.

The impact of the season on load demand, equipments limits and availabilities, is taken into account by dividing the year into three periods: summer (17% of the year), winter (25%) and mid-season (58%). A different probabilistic model is considered for each season. The transmission system un-availabilities are sampled independently according outage rates. Parameters of these distributions are derived from past records of planned maintenances and faults, aggregated for each type of equipment (e.g. 380 kV line, transformer, cable, etc). The global load level is determined according to its historical probability distribution. Such a distribution, referring to winter loads, is shown in figure 3, which represents on the horizontal axis the ratio of the load level with respect to the peak load and on the vertical axis the percentage of periods corresponding to a given load level.

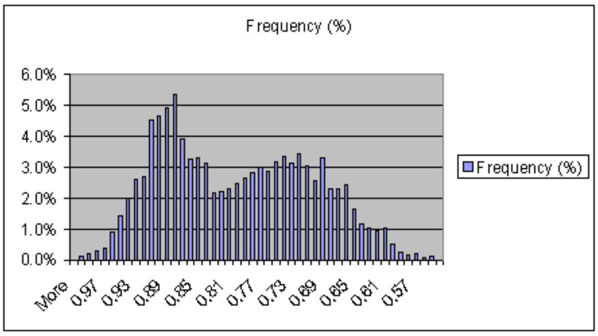

Figure 3: Winter load distribution

For each micro-scenario, the global load is distributed among individual substations and types of consumers. Each nodal load is computed by updating the corresponding base case value according to the macro-scenario hypothesis and the sampling result. A changing share of industrial/residential demand according to the season and the load level has been used.

Generating units are scheduled according to a pure economic criterion regardless of system constraints. The load to be dispatched is given by:

$$MW_{Load} * 1.02 - MW_{Import} = MW_{Dispatch}$$

where the 1.02 coefficient accounts for losses. If the available units are not sufficient to produce the required MW Dispatch, the lack is covered by additional import.

The OPF is used to compute the initial operating point by following the Belgian on-line tertiary voltage control algorithm. The desired operating point has to be: (i) acceptable: absence of voltage and current limit violations; (ii) feasible: respect of the control variable limits; and (iii) realistic: reactive power should be adequately distributed among the various units. The control variables of the OPF are: reactive generation of units, load tap changers settings, and shunt devices state. The objective is to maximise the reactive power reserve.

The five combinations of situations (one reference macro-scenario at t_O, two macro-scenario assumptions on the transit at t_{0+2}, two development options at t_{0+2}) together with the 997 reference micro-scenarios, leads to a total number of 4988 micro-scenarios.

3.3 Analysis

The analysis of the results was done in several iterative steps over a period of more than six months. All those steps and all the different considerations will not be reported in details in this article. We will rather focus on the analysis methodology and on some main interesting results produced by this methodology.

3.3.1 Convergence analysis of micro-scenarios

The OPF did not converge for every micro-scenario computed. In our methodology, we kept only the micro-scenarios that converged for every macro-scenario/reinforcement combination in order to carry out differential analyses among macro-scenarios. This leads in the end to 585 reference micro-scenarios out of 997. The histogram 4 shows whether a reference micro-scenario diverged at least for one combination or converged for the 5 combinations according to the load level at t_0.

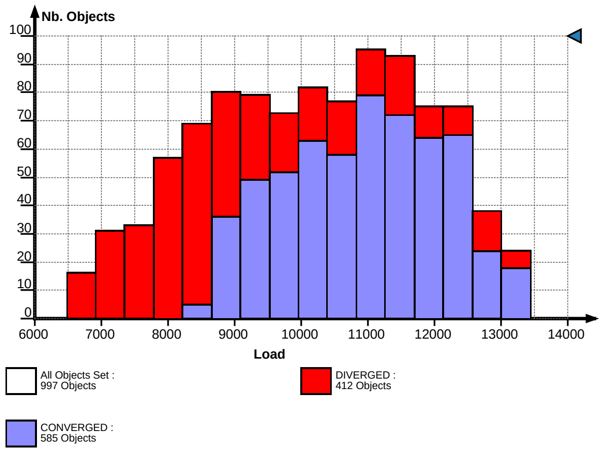

Figure 4: Convergence vs load at t_0

The bad convergence at low load level was actually explained (a posteriori) by two imperfections of the model. On one hand, the 1200 loads were modelled with a constant power factor and on the other hand, the small generation units are modelled as constant P-Q injections. The OPF is mainly responsible of the Mvar balance on the system. Because of this simplification, no feasible solution could be obtained by the OPF at very low load levels when the system generates a lot of Vars. The result is that the database of sound operating conditions is not really representative of low load situations. Nevertheless, we will see that interesting information could be extracted from the remaining micro-scenarios. The identification of the Var modelling problem was an unexpected byproduct of the study.

3.3.2 *Pre-contingency analysis of the micro-scenarios*

Table 1 gives for 3 macro-scenario/reinforcement combinations, the number of micro-scenarios with overflows in the pre-contingency state, the maximum, the minimum, the average and the variance of the current (A) for each overloaded equipment. In our example, the overloads have been classified in 3 categories:

- the overloads due to imperfections of the model;
- the problems already solved by the Belgian TSO but not implemented;
- the "new" overflows.

Equipment	#	Max	Min	μ	σ^2
t_0 , 1000 MW , no reinforcement					
Line 150.10	2	733.9	692.3	713.1	20.8
t_{0+2} , 1000 MW , no reinforcement					
Line 150.57	20	816.7	693.6	761.6	54.8
Line 150.10	1	715.1	715.1	715.1	0
Line 150.286	1	1696.3	1696.3	1696.3	0
Line 380.79	1	2122.0	2122.0	2122.0	0
Line 150.66	1	848.2	848.2	848.2	0
t_{0+2} , 1000 MW , reinforced					
Line 150.57	18	830.4	695.4	748.3	36.5
Line 150.10	2	791.5	686.1	738.8	52.7
Line 150.9	1	689.6	689.6	689.6	0
Line 150.131	1	1444.0	1444.0	1444.0	0
Line 150.66	1	870.3	870.3	870.3	0
Line 150.286	1	1734.8	1734.8	1734.8	0
Line 150.158	1	531.0	531.0	531.0	0

Table 1: Overloaded equipments in pre-contingency state

The table can be made for all the macro-scenarios together or macro-scenario by macro-scenario. Both kind of tables allow us to easily determine the 2 first categories of overloads while the second let us find out the differences between macro-scenarios and therefore "new" problems caused by either the increase of the load or the increase of the import or whether the network was reinforced or not.

Obviously, no TSO would accept to operate his network with overloaded equipments without taking any counter-measures. Therefore, those micro-scenarios already showing equipment overloads in the pre-contingency state have been individually analysed in details. After this analysis, they have been removed from the dataset so as to focus further analyses on the effect of contingencies.

This experience highlights that the analysis can only be performed by the people experienced in data mining together with the power system engineers in order to properly explain the phenomena.

3.3.3 *Filtering the contingencies*

In operational planning, the planning criterion of nearly each TSO aims at N-1 static security, i.e. for each network state with equipment(s) in maintenance, the loss of each remaining equipment must not cause overflows, voltage problems, etc. The analysis from this point of view has been carried out by first removing the micro-scenarios having violations in the pre-contingency state in at least one macro-scenario.

Equipment	nb	Max	μ	σ^2
Line 150.10	5002	169.4	109.4	7.0
Line 150.13	2893	135.1	103.5	3.2
Line 150.66	2147	135.8	104.0	3.8
Line 150.158	1897	139.1	105.3	4.7
Line 150.131	1516	141.1	103.7	3.2
Line 150.9	1464	165	108.8	8.7
Line 380.79	1236	127.4	104.0	2.8
Line 150.131	958	138.5	101.8	3.5
Line 150.127	955	138.5	101.8	3.5
Line 150.141	623	132.6	106.6	5.6
Line 150.14	613	135.7	105.6	4.9
Line 150.140	384	180.2	108.4	9.2
Line 150.19	195	138.2	104.4	7.8

Table 2: Overloaded equipments after contingency (%)

The results of the contingency analysis have been first analyzed using the same basic technique as we used in §3.3.1. Considering the 5 macro-scenarios together, Table 2 gives for each overloaded equipment the number of times the equipment has been overloaded, the maximum, average and variance of the percentage of current on the equipment (with respect to the permanent limit). This table provides us with the same kind of information as Table 1, but related to post-contingency states. Such analyses clearly highlight the weak points of the system, in terms of which elements are most often overload in the post-contingency state, throughout all macro-scenarios, or differentially for a given macro-scenario and a given reinforcement option.

Notice that, in our analysis, 2 other tables have been very useful to classify the overflows into the 3 categories: the most frequent outages causing overflows (i.e., the dangerous contingencies) and the most frequent outage/overloaded equipment combinations.

3.3.4 *Looking at some specific problems*

For some specific problems, the data mining has helped the power system experts to confirm or to get to the bottom of the phenomena. For an example, the 2 lines 150.10 and 150.9 are frequently overloaded. Notcie that these are actually two parallel transmission lines (we will refer to the two sub-stations they connect by sub-station H and sub-station R). 5 outages (contingencies) have been identified that cause overloads on those equipments.

A classical data mining technique [5] has been used to deepen the problem analysis. For the 5 outages, the percentage of current (with respect to the thermal limit) on the 2 lines together with information on the operating point has been extracted from the database and classified by a decision tree into insecure (at least one of the 2 lines overloaded) and secure situations. The outages on 150.10 and 150.9 are called *parallel* and the 3 remaining outages *other*.

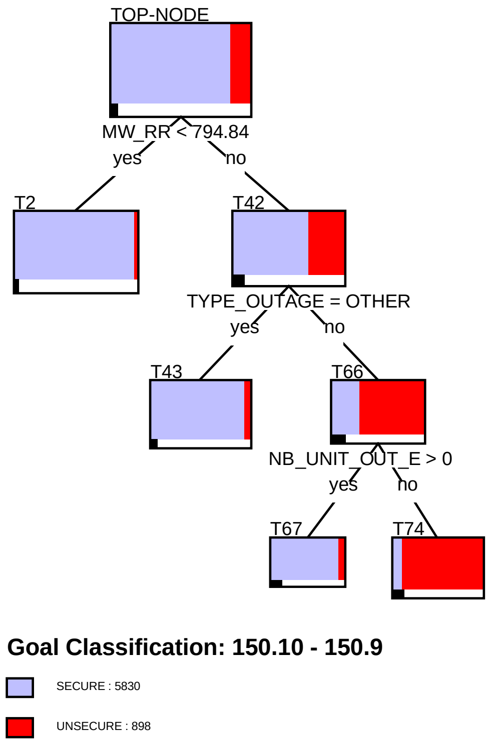

Figure 5: Pruned decision tree

The decision tree (6728 objects in the Learning Set, 1121 in the Pruning Set and 1121 in the Test Set, the error probability is 4.728%) represented on Fig. 5 confirms the experience of the power system engineers. The tree is read top-down, and each decision node is represented by a box showing in its upper part the percentage of secure and insecure scenarios in the training and in its lower part the test set error rate. The tree of Fig. 5 shows that a congestion on one of those 2 lines can be fixed either by stopping a generating unit at sub-station E or by switching on the parallel line or by decreasing the generation around sub-station R. We mention the fact that a reinforcement has already been identified to fix the problem, but it was not considered in this study.

3.3.5 Elaborating and using security indices

The power system engineers of the Belgian TSO wanted to challenge their own indices. Such indices have been computed for each micro-scenario. A first index consists in counting the number of overflows observed after a contingency (ND). Another index consists in summing up the overflows expressed in MVA of all equipments for all contingencies (SD). Combining those two indices leads to a third one, namely the average overflow expressed in MVA (AD).

The analysis has been done using histograms and scatter-plots like the one of Fig. 6 of those indices for the different macro-scenario/reinforcement combinations. At one point of the analysis, the utility of the reinforcement considered was impossible to determine, e.g. on Fig. 6 at time t_{0+2} with an import of 1000 MW the reinforcement seemed to generate problems since the index SD is often larger in the situation with reinforcement (i.e. point above the diagonal). On the other hand, with an import of 2000 MW the reinforcement appeared to be effective.

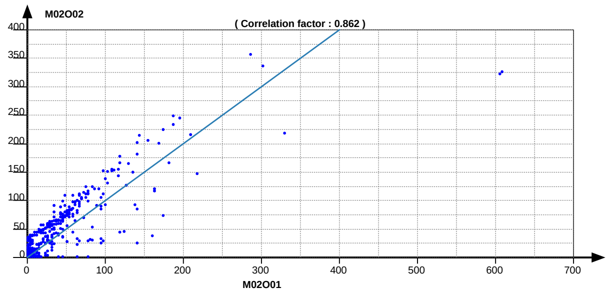

Figure 6: SD index: “no reinforcement” (on the x-axis) vs “reinforced” (on the y-axis). The macro-scenario corresponds to an import level of 1000 MW.

To deepen the phenomena analysis, the indices have been computed for 9 electrical regions (the 380 kV network, 8 parts of 220-150 kV network defined by the power system engineers according to their experience) and for 3 levels of overflow. On the Fig. 7, the 380 kV index confirmed the efficiency of the reinforcement (most of the points are located on the x-axis). The 220-150 kV indices revealed that half of the electrical regions are not influenced by the reinforcement, that one 220-150 kV region is relieved by the reinforcement and that several 220-150 kV regions are slightly weakened by the reinforcement. A specific analysis has been performed on those regions and the problems have been explained by the experts.

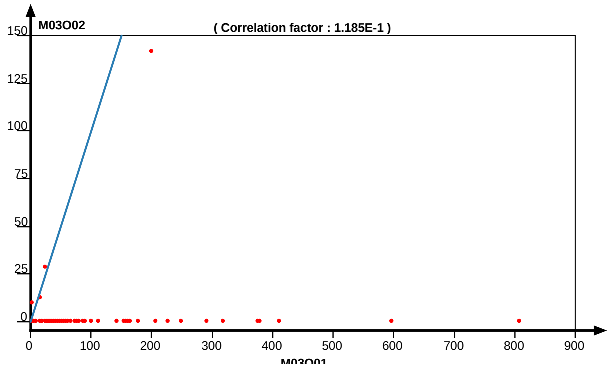

Figure 7: 380 kV SD index: “no reinforcement” (on the x-axis) vs “reinforced” (on the y-axis). The macro-scenario corresponds to an import level of 2000 MW.

4 CONCLUSIONS & FURTHER WORK

In this paper, we reported the application of the approach for expansion planning under uncertainties described in [7] on a real transmission expansion problem faced by the Belgian TSO. With respect to related works, in particular that of reference [6], this present paper provides a methodology based on the generation of a set of scenarios taking into account the temporal nature of the problem. The approach considers the major external uncertainties during the planning horizon as high-level hypotheses, the macro-scenarios, at different future time in635e4db1c9stants. The random nature of actual operating conditions, i.e. the maintenance of the transmission equipments and the availability of the generating units, is taken into account by using a probabilistic model based on past statistics.

The objective was to validate the efficiency of a transmission network reinforcement in terms of security margin with respect to the different high-level hypotheses. Our illustration has proven that our methodology was effective. Our example demonstrates that data mining techniques must be used by the power system engineers together with people experienced in data mining in order to properly explain the results, to identify the implied phenomena, to determine the causes and to find out the actual gain of proposed reinforcements. In the study we were able to “discover” some already known weaknesses of the system as well as some unexpected ones.

According to our experience, further efforts must be done regarding the power system model (load, embedded generation, phase-shifters, etc) in order to increase the convergence rate at low load levels, to facilitate the filtering phase by automatically evaluating additional reinforcements and to take into account preventive actions related to the maintenance instead of one unique topology.

This project has been developped by the University of Liège for the Belgian TSO within the framework of the Belgian TSO transmission expansion planning activities. This methodology is intended to be merged with other methodologies developped in parallel [8, 9]. The objective is to provide the TSO with the information about the efficiency and limits of the different future network reinforcements in a changing environment. The principal goal of the framework is to develop a complete methodology based on different techniques to investigate the opportunity, the efficiency, and the limits of network reinforcements in a long-term perspective. In the future, the approach could be enhanced by including a more complex market model in order to better evaluate the social welfare associated to the network reinforcements.

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