TOWARDS A PROBABILISTIC RISK ASSESSMENT OF DISTRIBUTED GENERATION CURTAILMENT IN SATURATED TSO/DSO NETWORKS

Farshid FAGHIHI
Université libre de
Bruxelles – Belgium
farshid.faghihi@ulb.ac.be

Pierre-Etienne LABEAU
Université libre de
Bruxelles – Belgium
pelabeau@ulb.ac.be

Jean-Claude MAUN
Université libre de
Bruxelles – Belgium
jcmaun@ulb.ac.be

Vanessa DE WILDE
Elia system operator – Belgium
vanessa.dewilde@elia.be

Arnaud VERGNOL
Elia system operator – Belgium
arnaud.vergnol@elia.be

ABSTRACT

A paradigm shift is in progress in the field of electrical energy production to increase the share of distributed generation. However, in many rural areas, grid operators are expecting more frequent line congestions and voltage problems. Active management of the distributed generation units is a solution to keep the grid secure: curtailment is applied to some generators in (almost) real-time in order to suppress congestion(s) on the grid. However, the impact of active management, in terms of e.g. expected curtailed energy per year, should be assessed before any possible new connection to the grid is allowed in planning phase. This paper proposes a pragmatic methodology to estimate these risk indices.

INTRODUCTION

For several years, global warming has become a world priority. One of the solutions proposed to mitigate this problem is the increased use of renewable energy for power generation. Regulations support this paradigm shift, for instance the EU Council in 2007 determined a target of 20% share of renewable energy sources by the year 2020. In addition, other types of distributed generation (DG), e.g. CHP (Combined Heat and Power) units, is increasing more and more in the new liberalized market. However, the traditional distribution grid infrastructure is designed for 'one-way flow' of electricity based on centralized production. Therefore, by increasing the amount of DG units, leading to 'two-way flow', grid operators are expecting more frequent line congestions and voltage problems in many rural areas. To solve this problem, the network should be reinforced; nevertheless it is an expensive and time-consuming task, which cannot be seen as a short-term solution. Alternatively, Active Network Management (ANM) is introduced. An ANM scheme controls the injection of energy produced by DG units to the grid in (almost) real-time in case of congestion(s) on the grid [1-2]. By this approach, the grid is retained secure.

Applying ANM provides the possibility of connecting more DG units to the existing network infrastructure before any reinforcement; however, the impact of ANM must be assessed before any possible new connection to the grid is allowed. Installing a new DG unit can lead to more energy curtailment of the current DG units. On the other hand, the risk of congestion on the elements of the grid should also be analyzed. Proper risk indices have therefore to be defined and calculated. Deterministic methods used for network calculations in system planning are however not suitable to assess these indices. Contrarily to the conventional generation facilities, DG units have intermittent production. This intermittency, in addition to the variability of consumptions, increases the number of the uncertainties affecting the system. The analysis of a system with numerous stochastic variables is only possible with probabilistic approaches. However, due to the large number of stochastic variables, it is not an easy task to properly cover the state space of the stochastic variables representing the working points of the system. For each *variant*, i.e. each possible combination of generations and loads, the N situation but also N-1 situations are analyzed. Therefore, the number of states of the network to be analyzed dramatically increases.

Two types of methods are proposed in the literature to tackle this problem, i.e. Monte Carlo Sampling (MCS) and the multi-state approach (MSA). MCS is based on sampling variants from the joint probability density function (pdf) of the uncertain parameters. However, due to the non-linearity of the problem and the high dimensionality of the variant space, the sample size should be extremely large. Each sample serves as input data for an Optimal Power Flow (OPF) module to calculate the possible re-dispatching or curtailment of DG units. In order to control the number of variants, the MSA [3] is related to a discretization of the stochastic variables in order to define the different possible combinations of discretized loads-generations that are significantly different, with respect to causing congestions. However, to control the number of variants, some simplifications are made. For instance, correlation coefficients between productions of all wind farms are considered to be equal to 1. The same assumption is made for the loads. These assumptions possibly lead to an oversimplification of the problem.

This paper proposes a pragmatic methodology to handle the high dimensionality of the problem and estimate the impact of connecting a new DG unit, via the computation of several risk indices. A systematic approach guarantees searching all over the plausible congestion zones of the state space, while an on-target sampling drives the computational effort towards the direction of interest. This combined approach allows managing the computation time.

This paper is organized as follows. First the steps of the proposed methodology are explained, and then the results obtained on a test case are presented. The final section is dedicated to the conclusions.

METHODOLOGY

The flowchart of the methodology is shown in figure 1.

Modeling uncertainties

The uncertainties are generations and loads. The stochastic behavior of the uncertainties is modeled by eliciting their joint pdf. Some uncertainties are moreover correlated. Loads at the different nodes are correlated because of the interdependency between consumptions due to either similar weather conditions or same daytime. Furthermore, the powers produced by wind farms are also correlated due to dependency on the wind speed in the area. Therefore, for correlated uncertainties, a joint pdf has to be constructed. It is determined by resorting to a *Copula* i.e. "a function that joins or couples multivariate distribution functions to their one-dimensional marginal distribution functions" [4-5].

Merging uncertainties

In order to reduce the dimension of the problem, the uncertainties are first grouped in new variables called the *net balances*. The net balance at a given node is the algebraic sum of all productions ΣP minus the total load ΣL in this substation at any time.

The plausible domain of interest for the study is first determined in the net balance space. This domain can be divided into a safe and an unsafe region, in terms of combinations of net balances making congestion on the grid. To provide an estimation of the unsafe region, the net balance domain is discretized and analyzed in order to find unsafe cells, i.e. cells for which inputs can cause congestion. The probability of each unsafe cell is calculated next, as well as the expected curtailment associated with variants lying in this cell, by MCS. Finally, risk indices are calculated by summing on all unsafe cells the expected curtailment weighted by the corresponding cell probability.

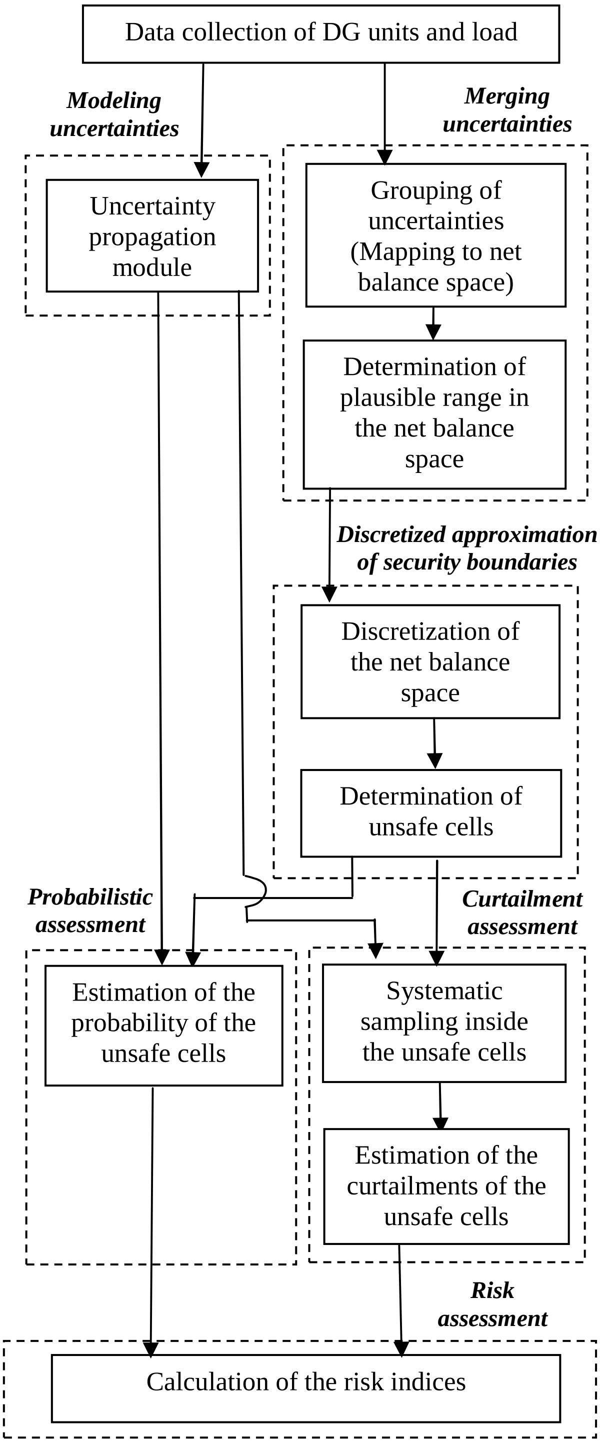


Figure 1. Methodology overview

Moving from the detailed variant space to the net balance space merges the uncertainties, based on their similarity in making congestion on the grid. After merging, we benefit from a dramatic reduction in the dimensionality of the problem. The variant space and the net balance space can be mapped together. Each point in the variant space corresponds to a point in the net balance space; however a point in the net balance space corresponds to more than one point in the variant space. The plausible domain of interest in the net balance space can be determined considering the maximum and minimum of generations and loads.

As shown in figure 2, there is a security boundary that divides the net balance space into a safe and an unsafe region. The safe region corresponds to the net balances of all variants that make no congestion on the grid, while the unsafe region is related to the mapping of the variants that make congestion, to the net balance space. A considerable part of the net balance space belongs to the safe region and can be skipped in further analysis. On the contrary, the sampling should be forced into the unsafe region where curtailment(s) are required. It should be noted that for the N and each N-1 situation, security boundaries are different, due to different possibilities of congestion in each topology. The next section deals with how these security boundaries can be approached.

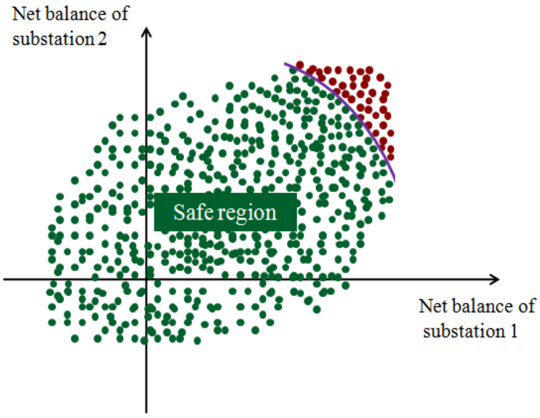


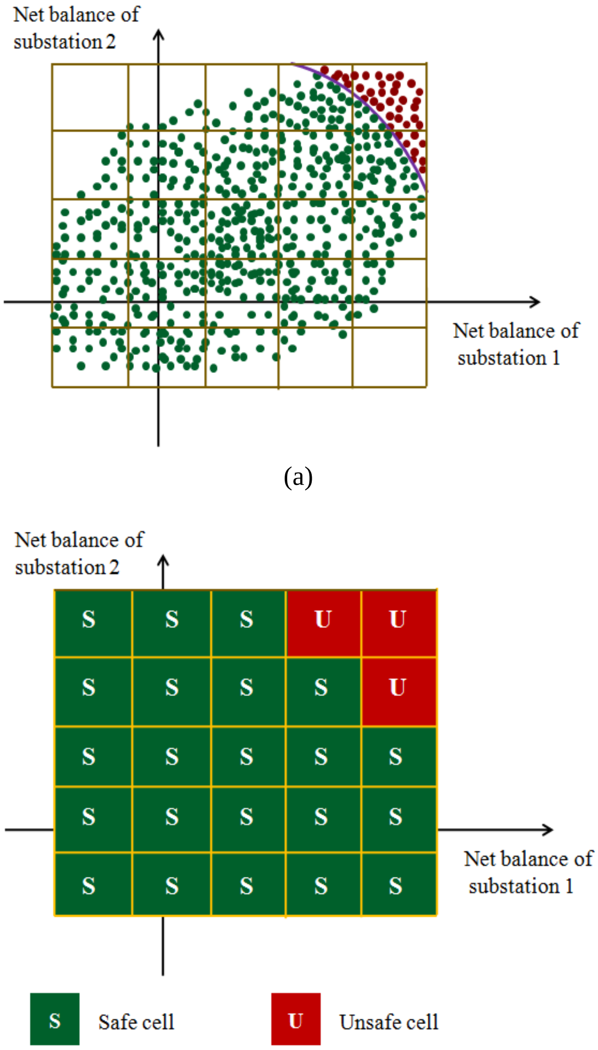
Figure 2. Net balance state space

Discretized approximation of security boundaries

Due to the high non-linearity of the problem, approaching the security boundaries by a mathematical model is impossible in practice. As a solution, a discretization approach is applied by the definition of a mesh (see figures 3a-3b). The distinction between the safe and unsafe cells is achieved by applying a load flow (LF) calculation on the variants located at the corners of the cells. Those variants leading to overload in both N and N-1 situations are identified by this approach. If all the corners of a cell are safe (i.e. cause no congestion), then the cell is considered as safe, otherwise it is assumed to be unsafe. The sampling can be performed only in the unsafe cells.

Curtailment assessment

Once the unsafe cells in the net balance space are identified, these cells are mapped to the variant space. A systematic sampling inside the unsafe cells generates variants corresponding to the unsafe region. The curtailments of the DG units for each variant are calculated by an OPF tool. The expected value of each DG unit's curtailment is estimated in this way for each unsafe cell. In this procedure, different costs of curtailment can be assigned to the different DG units via the objective function of the OPF. Principles of access (PoA) can also be respected in the curtailment calculation. PoA define the priority of curtailment of the DG units contributing to the same congestion. Different PoA can be defined depending on the location of the congestion (HV grid and/or HV/MV substation).



(a)

S	S	S	U	U
S	S	S	S	U
S	S	S	S	S
S	S	S	S	S
S	S	S	S	S

🟩 S Safe cell 🟥 U Unsafe cell

(b)

Figure 3.a. Discretized approximation of the security boundary- 3.b. Identification of safe and unsafe cells

For instance, a technical optimum can be chosen to handle the overloads on the HV grid and a LIFO scheme could be applied at the substation level in order to distribute the amount of required curtailment (due to overloads on HV grid on one hand and to HV/MV transformers on the other hand).

Probabilistic assessment

The objective is to estimate the probability of the unsafe cells in the net balance space. The first step is to generate samples from the joint pdf of the correlated uncertainties. MCS is applied in this step to produce a huge number of correlated samples. Those correlated samples are related to the power produced by the wind farms but also to the loads. However, the possible number of states obtained by combining the production of DG units and the loads may lead to a non-manageable sample size due to combinatorial explosion. Therefore, a discretization on the space of the correlated samples is performed by defining a mesh to generate a limited (but reasonable) number of states. The center of each cell in the mesh represents all the samples inside the cell, and the ratio of the number of samples inside the cell over the total number of samples determines the cell probability estimation. This procedure is repeated for all the correlated uncertainties. The next step is to combine these discretized states by the rule of product and to convert them to the corresponding net balance value. Finally, the probability of each unsafe cell is calculated considering the mapped variants to the cell and related probabilities.

Risk assessment

Up to now, the unsafe cells were identified and the probability and curtailment of the cells were estimated. Risk is generally defined as the product of consequence and probability. Therefore, the risk of curtailment can be calculated by summing on the unsafe cells, the expected curtailment associated to the cell weighed by the corresponding probability. Having the risk of curtailment for each DG unit, the utilization factor (UF) of each unit can be calculated. The UF of a DG unit is the ratio of the actual energy produced in one year over the corresponding theoretical maximum. The UF of a DG unit is an economic factor that characterizes the relevance of the investment for a producer. In addition to the mentioned indices that describe a mean value of curtailment during a year, the distribution of the curtailment can also be provided. By considering the amount of overload on the assets in the unsafe cells and the corresponding cell probabilities, the total risk of congestion can be calculated as well. The distribution of the congestion on each element of the grid can also be estimated. All these indices can be calculated explicitly for the N and all N-1 situations of interest.

RESULTS

The method is applied on a test case with 3 substations, 5 wind farms (total capacity: 52 MW), 3 CHP units (total capacity: 35 MW) and one load in each substation (see figure 4). For the purpose of our test case, all DG units are assumed to be connected to the MV side. Although the network is simply made of 3 lines and 3 substations, the load and production profiles are inspired from a real case. Risk indices are estimated for the N and intended N-1 situations, as well as for all defined seasons in a year. The N-1 situations are related to the outages of HV/MV transformer in substation no. 2 and each HV line. The analysis is performed for 3 seasons, i.e. summer, inter-season and winter. For each season, different ratings are considered for the grid elements. The probabilities to be in summer, inter-season and winter are considered to be 0.25, 0.5 and 0.25, respectively. A probability of outage of each line and each HV/MV transformer is assumed as well.

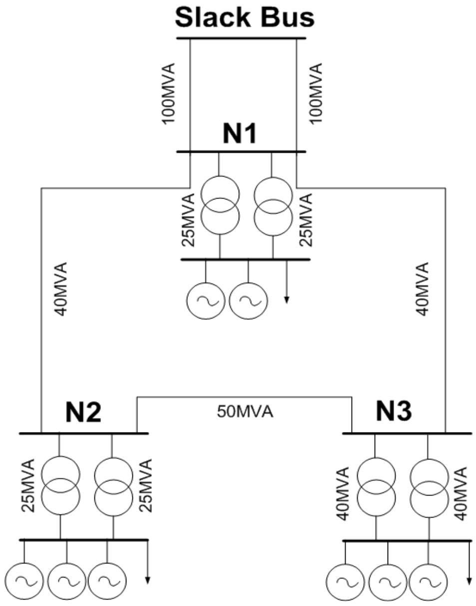


Figure 4. Test case

The distributions of the curtailment in a wind farm due to outage on the HV grid and HV/MV transformer in substation no. 2 are shown in figures 5 and 6, respectively. A detailed analysis can also be provided for the distribution of the curtailment of each DG unit in N and each N-1 situation in each season. The distribution of the congestion on a line in a N-1 situation on the HV grid in summer is shown in figure 7. A detailed analysis can be provided for distribution of congestion on each asset in N and all N-1 situations in each season.

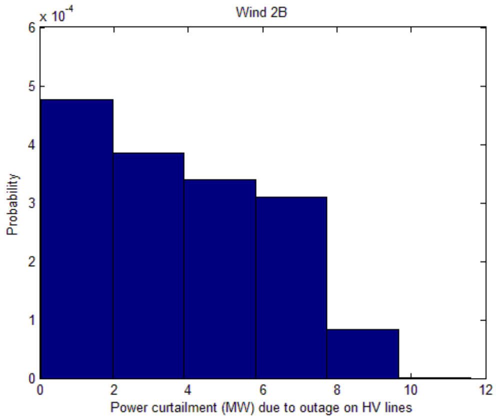


Figure 5. Distribution of the curtailed power in a wind farm due to outage on HV lines

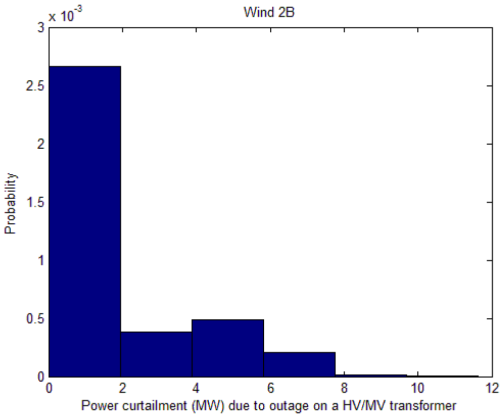


Figure 6. Distribution of the curtailed power in a wind farm due to outage on a HV/MV transformer

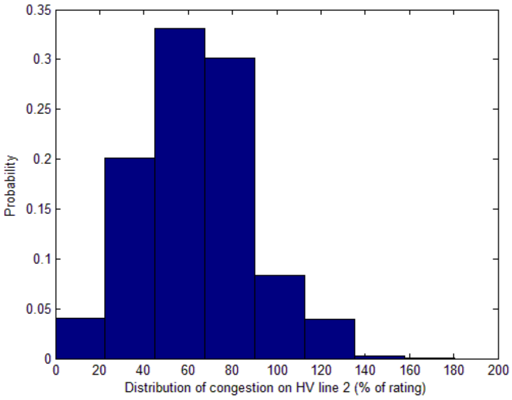


Figure 7. Distribution of the congestion on a line in a N-1 situation on the HV grid in summer

CONCLUSIONS

The share of DG in electricity production is increasing. Both TSOs and DSOs face more challenges, in terms of congestion and voltage problems, due to 'two-way flows' at the distribution level. Modern grids should evolve to handle these challenges, before a possible grid reinforcement. ANM, in the context of smart grids, is introduced as part of this evolution by controlling the injection of energy produced by DG units in case of security problem on the network.

However, in the planning phase, the impact of ANM should be assessed before any possible new connection to the grid is allowed. Any new DG unit can affect the curtailment of the other DG units installed in the area and the risk of curtailment of each producer (in N and N-1 situations) has therefore to be assessed. Due to the intermittent production of DG units, probabilistic approaches are developed to handle the problem. However, by increasing the number of stochastic variables (associated to not only the DG but also to the loads) the complexity of the problem increases. This paper proposed a pragmatic methodology to assess risk indices characterizing an ANM scheme performance by a systematic approach. The idea is based on grouping uncertainties based on similarity in making congestion on the grid. A new less dimensional state space, i.e. the net balance space, is constructed. The unsafe region in this space is identified and mapped to the initial high-dimensional variant space. The main advantage of this approach is to drive the sampling towards regions of interest in the search space. The unnecessary analyses are skipped. The results are categorized into two main groups, i.e. risks related to the curtailment of DG units and the risk associated with congestion on the grid elements.

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