Planning in Transmission Systems with a Great Level of Penetration of Distributed Generation

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***Abstract*— This paper presents the methodology implemented in UTE for the transmission system planning based in probabilistic load flows considering the variability of distributed generation. The motivation arises to migrate from a deterministic to a probabilistic planning method, using for the analysis the software developed in UTE, EPPTRA. A new way to assess the 150 kV transmission lines chargeability is proposed, which allows a better use of the system capacity.**

***Index Terms*— Probabilistic Load Flow – Distributed Generation - Transmission.**

I. INTRODUCTION

Historically in UTE, steady state studies for medium term transmission system planning have been performed in a deterministic way, based on worst case scenarios. These worst cases are configured combining demand and generation scenarios, analyzing for each case whether the load flow presents overloads in the transmission system elements or out of range voltages in the transmission buses. The configuration of these worst case scenarios is based on the experience of the specialist in charge, as to how power flow will distribute in the system, and on historical generation dispatches. Until recently, there were essentially two types of generators in the Interconnected National System (Spanish acronym: SIN): thermal and hydraulic generators. Thermal power plants, with a total installed capacity of approximately 1500 MW, are basically concentrated in the area of Montevideo, and hydraulic power plants, with a total installed capacity of 1500 MW, are grouped along the Black River, in the centre of the country, in addition to Santo Grande Hydraulic Power Plant, which is located on Uruguay River at northwest of the country. Because of this, generation scenarios were simply summarized in hydraulic, thermal or mixed. Load flow patterns in the transmission system were the result of combining these generation scenarios with extreme demand scenarios (summer or winter system maximum demand of approximately 2500 MW, system minimum demand of approximately 1000 MW).

Nowadays, wind and photovoltaic generation is beginning to be incorporated to the system. In the short term, a great amount of this type of generation is expected to be incorporated to the system. For the year 2020, approximately 1500 MW of wind generation and 250 MW of photovoltaic generation are expected to be connected to the system. This generation is geographically distributed all along the country, and it is connected to various distribution and transmission systems nodes. Additionally, new transmission lines are planned to be built in the system, transforming the current purely radial network of the north of the country into a meshed one; as well as the incorporation of Melo frequency converter, with an interconnection capacity of 500 MW, which increases significantly the capacity of the interconnection between Uruguay and Brazil.

The change in the system topology and the amount of distributed generation expected to be incorporated, modifies in a very significant way the load flow patterns, introducing a great level of uncertainty in the generation scenarios and enormously increasing the amount of possible worst case scenarios to be considered in a planning study of the transmission system. Under these conditions it becomes extremely difficult for a specialist to configure worst case scenarios and therefore to perform the planning study.

Consideration of uncertainty in power systems has been presented in a vast number of papers, being introduced the concept of probabilistic load flow [1]. The technique commonly used is based on the Monte Carlo method, where a series of simulations are repeated drawing the random variables. Some applications require a large number of simulations and a significant computational time, which has derived in several technical papers which propose different analytic methods to solve the problem of probabilistic load flow [2].

Nowadays, the great penetration of renewable distributed generation in power systems as drawn interest of utilities in probabilistic techniques, however, its application is mainly concentrated in the academic world, being incipient the development of applications for industrial use and its consideration in the transmission systems planning [3].

At the light of this new scenario UTE has migrated from the deterministic planning of the transmission system, based on the analysis of a reduced number of cases, to planning based on

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probabilistic load flow, considering expected scenarios in the medium term.

II. Probabilistic load flow

To analyse the system´s performance in the medium term taking into account the variability of distributed generation, UTE has developed EPPTRA, a software tool which allows obtaining the probability density for the load of each of the system´s elements and identifying the different load patterns, from the study of a great number of cases.

A case is defined by the combination of the power injected into the system by each generator and the power consumed from the system by each load, at a given time, and it can be represented in vector form as follows:

$$c_i = (G_{i,1}, \dots, G_{i,u}, \dots, G_{i,g}, D_{i,1}, \dots, D_{i,v}, \dots, D_{i,d}) \qquad (1)$$

where:
$G_{i,u}$ is the power injected into the system in case i by generator u
$D_{i,v}$ is the power consumed from the system in case i by load v.

Power consumed for each case is obtained from the Interconnection National System (Spanish acronym: SIN) aggregated demand projection model used by UTE.

Power injected by renewable generators is obtained from the random variable used to model the resource (wind speed or solar irradiation. Random variables are drawn considering the historical series probabilistic distribution and correlation (wind speed and solar irradiation measurements).

Power of thermal generators and hydraulic generators with reservoir are associated with economical optimum dispatch. The power associated to each generator in the system is an input data for EPPTRA and are obtained from an energetic simulation generated for each hour of the year under study. This simulation is obtained using SimSEE software tool [4], which aims to minimize the future cost of demand supply and with tens of thousands of cases are obtained.

A. DC load flow

Considering the system´s distribution factors matrix obtained from software PSS/E (software in which the complete SIN is modelled), the DC load flow on each element of the system can be calculated directly using matrix algebra, for any "n" cases, as follows:

$$\begin{bmatrix} G_{1,1} & \dots & G_{1,g} & D_{1,1} & \dots & D_{1,d} \\ \vdots & & \vdots & \vdots & & \vdots \\ G_{i,1} & \dots & G_{i,g} & D_{i,1} & \dots & D_{i,d} \\ \vdots & & \vdots & \vdots & & \vdots \\ G_{n,1} & \dots & G_{n,g} & D_{n,1} & \dots & D_{n,d} \end{bmatrix} \begin{bmatrix} f_{1,1} & \cdots & f_{1,e} \\ f_{2,1} & \cdots & f_{2,e} \\ \vdots & \ddots & \vdots \\ f_{(g+d),1} & \cdots & f_{(g+d),e} \end{bmatrix} = \begin{bmatrix} F_{1,1} & \dots & F_{1,e} \\ \vdots & & \vdots \\ F_{i,1} & \dots & F_{i,e} \\ \vdots & & \vdots \\ F_{n,1} & \dots & F_{n,e} \end{bmatrix} \qquad (2)$$

where:
$G_{i,u}$ is the power injected into the system in case i by generator u
$D_{i,v}$ is the power consumed from the system in case i by load v.
$f_{w,l}$ is the distribution factor of the generator or load w through element l
$F_{i,l}$ is the power load flow through l in case i.

From the analysis of the DC load flow of the totality of the cases described before, the load probability density of each element of the system can be calculated, particularly the overload probability and the maximum load for each element.

B. *Chargeability representative load flow patterns*

The chargeability analysis considering reactive power flow and voltages in system nodes implies solving AC load flows, but the time it would take to perform all these AC load flows for the large number of cases involved, is not compatible with the planning working dynamic. It is therefore necessary to reduce the number of cases to be solved, selecting in an adequate way those cases which are representative of the system´s behavior.

The transformation shown in (2) allows to take the cases from the vector space of injected and consumed power per node to the vector space of DC flow per system element. Cases which are not "far" from each other considering the Euclidean distance in this new vector space, will have a similar power flow pattern.

Using CLARA algorithm [5], which uses a partition clustering technique based on PAM algorithm [5], cases are grouped in a predefined number of clusters(k). A cluster is formed by a case denominated medoid and those cases with the smallest Euclidean distance to that medoid. Each cluster represents a system´s power flow pattern and will be represented by a medoid. The probability represented by each of these k medoids is determined as a function of the cases which belong to each cluster:

$$p_{cluster_j} = \sum_{i=1}^{n} p_{case_i} \cdot \mathbf{1}(case_i \in cluster_j) \qquad (3)$$

where:
$p_{cluster_j}$ is the probability of cluster j
p_{case_i} is the probability of case i.

Prior to the clustering selection and for a correct selection of clusters, the DC load flow is normalized with respect to the rated capacity of each system element.

Fig. 1 presents an x/y graph of a 16 cases example. In the x-axis DC power flow through element 1 is shown and in the y-axis DC power flow though element 2 is shown, both expressed as a percentage of the rated capacity of each element. Applying the clustering technique for k=3 in this example, three clusters are obtained, where each cluster is represented by its medoid, shown as triangles in Fig. 1. It is clear that choosing medoids as representative cases for the entire cluster does not allow a great level of detail regarding the maximum load of system elements. As it can be seen in the example, the case where element 1 reaches a load of 120% is represented by a medoid in which the element only reaches

90% of its rated capacity. In order to have greater detail regarding the maximum load of the system elements, the *m* cases where maximum load for each system element is reached are added to the *k* medoids selected by CLARA. Using this k+m cases as medoids the totality of the cases are classified again and probabilities for each cluster are re calculated. Fig. 2 presents clusters obtained after adding as medoids those cases in which the maximum load of system elements is reached.

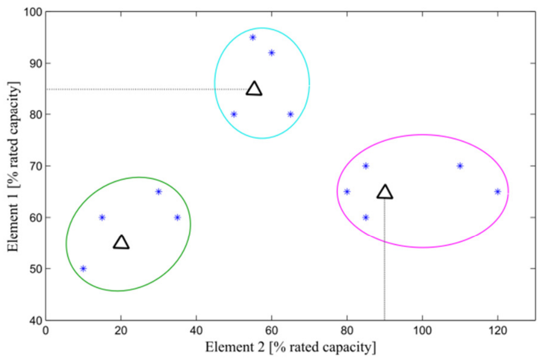

Fig. 1. Grouping example,16 cases, k=3 medoids.

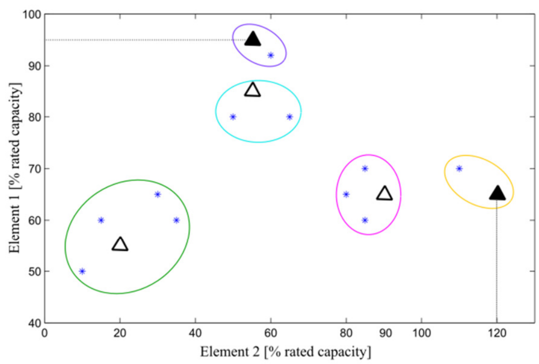

Fig. 2. Grouping example, 16 cases with k=3 and m=2 medoids.

It can be obtained, therefore, a reduced number of cases which are representative of the different power flow patterns, and an estimation of how frequent these patterns are in the behaviour of the system.

The technique applied is adequate to contemplate the diversity of load flows present in the system and to evaluate its behaviour from the point of view of the elements´ load.

III. 150 kV Overhead lines Overload Criteria in Probabilistic Load Flow

A. Introduction

The limit for overloads in 150 kV overhead lines in Uruguay is defined by the electrical discharge risk when the conductor sag increases, and not by the conductor´s damage risk. According to international standards, it is not acceptable for the sag to be less than a certain value under no circumstances. However, it is possible to accept conductor temperatures higher than the design value, increasing the thermal risk without increasing the accident probability (discharge probability), considering the minimum distance between the conductor and the ground has a security factor with respect to the minimum value established by the standards. UTE has defined criteria which simultaneously limit the maximum overload and the overload probability, which allows obtaining the maximum use of the system´s capacity.

B. 150 kV overhead lines overload criteria in Uruguay

Given that the main limitation of the Uruguayan transmission system is the steady state current capacity of 150 kV overhead lines, UTE has prioritized to define an evaluation criteria which allows defining whether current values obtained with EPPTRA are acceptable or not.

The majority of 150 kV overhead lines in Uruguay have been designed for a conductor´s maximum temperature of 55 °C. For this relatively low superficial conductor temperature, chargeability criteria are based exclusively in controlling the distance to ground of the conductors. These distances are defined in Uruguay using the NESC code [6]. In accordance with this code, overhead lines of voltages of up to 170 kV must respect a minimum distance to the ground of at least 6.4 m in areas where it is possible for agricultural machinery to pass by. This minimum distance is calculated considering a vehicle of a typical height and an electrical safety distance of 1.52 m.

All 150 kV overhead lines in Uruguay have been designed considering a minimum distance to the ground of 7 m, so there is a security “buffer” of 60 cm with respect to the NESC distance. Assuming an error of up to 30 cm between the real line´s sag and the sag considered during the design of the line [7], it is safe to assume an effective security “buffer” of 30 cm.

C. Accident probability

Since the violation of the minimum distance to the ground of an overhead line implies a risk of an electrical discharge, overload criteria is based on the concept of “discharge probability” [8]. The idea is to identify the different random variables which might have an effect on the event of an electrical discharge of the line, and to estimate their corresponding probabilities. The probability of an electrical discharge of the line associated with certain design of the line and certain overload criteria is defined combining these probabilities.

The probabilities adopted for the random variables associated with overhead lines design in Uruguay is not exactly known, reason why typical values have been assumed, based on the literature. Given that there is no record of accidents caused by insufficient distance to the ground of overhead lines in Uruguay, it is also assumed that overhead lines have been designed considering an adequate value for the discharge probability.

Any overload criteria which might be adopted for planning studies cannot therefore reduce the discharge probability currently in use.

Criteria adopted in EPPTRA are based on the analysis of two of the random variables at stake: conductor´s temperature and withstand of the electrical distance between the conductor and the object under the line. The remaining random variables involved (height of the object under the line, overvoltage considered in the design, etc.) are considered with probabilities equal to the ones assumed for the design of the line, whatever their values may be.

Expressing this in mathematical terms:

$$p(Acc) = \mathrm{p(gap)\ x\ p(TC)\ x\ K} \quad (3)$$

where :
$p(Acc)$ is the discharge probability
p(gap) is the electrical distance withstand probability for a given overvoltage
p(TC) is the probability for the conductor´s temperature to be higher than the design value
K, is the probability of occurrence of the other random variables involved.

D. Electrical distance withstand

As it has already been said, the electrical distance adopted (hereinafter, D) in the NESC code for 150 kV overhead lines is 1.52 m. The design overvoltage associated with this "gap" is a fast front overvoltage (atmospheric discharges), and it is withstood by distance D with a discharge probability p(gap) equal to 0.001 [9].

The overload criterion adopted assumes it is possible to increase distance D in such a way the discharge probability tends to zero p(gap)≈0. To this end it is enough to increase D in order the discharge probability deviates four standard deviations from the mean value. The corresponding calculation gives a value of D equal to 1.57 m, and in a conservatory way a slightly bigger value has been chosen: 1.62 m.

E. Conductor´s temperature

The conductor´s temperature is conditioned by two random events, RT and SC:

- RT: RT is the event in which the weather conditions (ambient temperature, wind, solar radiation) are worse than the ones considered in the line´s design.
- SC: SC is the event in which the current circulating in the conductor is higher than the current considered in the line´s deign

Expressing this in mathematical terms:

$$p(TC) = \mathrm{p(RT)} + \mathrm{p(SC)} - \mathrm{p(RT)\ x\ p(SC)} \quad (4)$$

In order to choose an overload criterion for EPPTRA it is necessary to select a the maximum admissible value for p(SC), which has been done considering the following hypothesis:

a. Fix p(RT) equal to 0.01. This value for p(RT) is a typical value adopted for overhead lines designed with "worst case" criteria for weather conditions [7], which is the case of overhead lines in Uruguay.

b. Impose that the probability of the two events RT and SC happening simultaneously is negligible. This criterion imposes the following mathematical restrictions:

$$p(SC) \ll \mathrm{p(SC)\ x\ p(RT)} \quad (5)$$

and

$$p(RT) \ll \mathrm{p(SC)\ x\ p(RT)} \quad (6)$$

There are no other restrictions to choose p(SC), given that when p(gap) ≈0, the discharge probability p(Acc) is practically not affected by p(TC).

By means of a "trial and error" process performed with several studies done with EPPTRA, it has been found that a value equal to 0.05 for p(SC) is reasonable for the Uruguayan system.

F. Maximum overload limitation

As a part of the overload criteria adopted, is has been imposed the common restriction that under no circumstances overhead lines violate security distance NESC [7], which is increased in 10 cm in accordance with the stated above. The 30 cm "buffer" is reduced to therefore to 20 cm. For most of the 150 kV overhead lines in Uruguay, accepting the conductors go down 20 cm is equivalent to accepting over temperatures of approximately 8 °C, and overloads of approximately 25 % with respect to the current design.

G. Summary

The overload criteria for 150 kV overhead lines to be applied in studies performed with EPPTRA are therefore:

- Maximum overload probability: 5 %
- Maximum overload: 25 %

IV. Voltage Regulation Analysis

Problems associated with voltage regulation in the system must be analysed by means of AC load flows. To reduce the number of cases to be analysed, the same clustering technique explained before over the results of DC load flows could be used, but cases analysed might not be a good representation of the different voltage patterns. Techniques which allow the selection of cases which are representative enough for these studies are currently being developed in UTE.

V. Conclusions

The analysis of the transmission system by means of probabilistic load flow is adequate to address planning studies for the Uruguayan transmission system with a great level of distributed generation penetration. This methodology allows considering a great number of cases, combining generation and demand, where not only the electrical model of the system is considered, but also the interaction between the variables responsible for the power load flows.

EPPTRA allows analyzing the load of system elements in a great number of cases, which would be unmanageable using the traditional methodology, where each case was configured and analyzed by a specialist.

The clustering technique applied over the DC load flows results allows reducing the number of cases to be analyzed using AC load flows, selecting the most representative cases considering the different load flow patterns.

As not only the maximum overload value is obtained, but also the overload probability is estimated, it is possible to adjust the planning criteria considered when deterministic planning was performed and obtain therefore a better use of the capacity of the transmission system.

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