Dealing with Uncertainties in Long Term Transmission Expansion Planning Problems

A. S. Braga[1], and J. T. Saraiva[2], *Member, IEEE*

***Abstract* — Transmission expansion planning corresponds to a very relevant issue that should not be forgotten in the scope of the implementation of market mechanisms in the electricity sector. This paper describes a multicriteria model to perform transmission expansion planning exercises that combines probabilistic models to represent the reliability of system components with fuzzy models to incorporate the uncertainty on load evolution along the planning horizon. This formulation also outputs long-term marginal prices that can be used to compute the Marginal Based Remuneration. The paper includes a case study based on the Portuguese 400/220/150 kV transmission network.**

***Index Terms* — Transmission expansion-planning, uncertainties, probabilities, fuzzy sets, Simulated Annealing, long-term marginal prices.**

I. Introduction

In several countries, the electricity sector went through a restructuring and liberalization process that has been placing several challenges to agents acting in the sector. Among them, the development of tariff approaches to remunerate the use of networks in general, and transmission networks, in particular, is certainly one of them. The literature on this topic includes a vast number of publications regarding methods to allocate the cost of using the networks to the users. These methods can be gathered in three main approaches: embedded cost average methods, incremental approaches and marginal ones. Among them, marginal methods are the most interesting ones given their technical robustness and their ability to transmit economic signals to the network users in order to induce higher efficiency levels. They are based on the calculation of nodal marginal prices reflecting the impact on the objective function of having a change in a given bus load.

Nodal marginal prices [1] can have a short or a long-term nature depending on the time horizon involved. In the first case, the objective function only includes operation costs, while in the second it also reflects investment costs. Short-term marginal prices are typically very volatile and they typically lead to the Revenue Reconciliation Problem [2,3] as they only allow the recovery of a small percentage of the regulated costs of a transmission company. On the contrary, long-term marginal prices inherently address these problems since they are much more stable along the horizon – they include a long term trend due to investment costs – and the revenue problem is eliminated – once again due to the incorporation of investment costs in the objective function. However, long-term marginal prices are more complex to compute as that they require solving a long-term expansion problem. Transmission expansion problems are very complex to address as they are multi-period, dynamic and discrete and they are affected by several uncertainties.

This paper describes a mathematical formulation to the transmission expansion problem addressing in an holistic way the issues just referred. Investments are treated in a discrete way, it incorporates uncertainties affecting the reliability of system components and the load evolution along the horizon and it displays a multicriteria nature. The paper is organized as follows. After this introductory section, Section II briefly describes Simulated Annealing, since this was the used optimization tool, Section III details the formulation of the problem, Section IV describes the solution algorithm, Section V describes the computation of nodal marginal prices, Section VI presents the case study based on a real transmission network and Section VII draws the most relevant conclusions.

II. Simulated Annealing – An Overview

In the last decade, several optimization techniques emerged both in conceptual terms and in current applications often called metaheuristics. Simulated Annealing is just an example of one of them. It can be used to address combinatorial problems, CP, due to the presence of discrete variables. Traditionally, this type of problems was tackled in a two-step approach. In a first phase, discrete variables were relaxed into continuous ones, and then the output was rounded to the nearest integer. This approach has the fundamental drawback of not ensuring that this integer solution corresponded to the optimal one. Other approaches adopted branch-and-bound based techniques, usually leading to a large amount of computation time. It should also be referred that several continuous optimization algorithms – as gradient based techniques – have the conceptual problems of converging to local optima also very frequently depending on the initialization conditions. However, in several real life problems, decision makers are frequently not interested in the global optimum. This real life characteristic diminished the accent on global optima and emphasized the concept of good engineering solutions.

Simulated Annealing was developed by Kirkpatrick et al based on the Metropolis algorithm [4,5] dated from 1953. It is a search procedure that includes the possibility of accepting a solution worse than the current one. The algorithm starts at an initial solution, x_1, evaluated with an evaluation function, $f(x_1)$. Then, it samples a new solution in the neighborhood of x_1. If the new solution improves $f(x_1)$, the new solution is accepted. If it is worse, it can still be accepted depending on a probability of accepting worse solutions. This mechanism aims at introducing diversity in the search procedure as well as allowing the iterative process to escape from local optima. In a more formal way, the algorithm is summarized as follows.

(1) A. S. Braga is with Instituto Politécnico da Guarda, Escola Superior de Tecnologia e Gestão, Av. Francisco Sá Carneiro, no. 50, 6300-559 Guarda, Portugal, braga31@sapo.pt

(2) J. T. Saraiva is with Faculty of Engineering of Porto University and with the Power Systems Unit of INESC Porto, Rua Dr. Roberto Frias, 378, 4200-465, Porto, Portugal, jsaraiva@fe.up.pt.

Simulated Annealing Basic Algorithm

i) Initialization: Select an initial solution x_1 in the solution space X. Evaluate x_1, $f(x_1)$;

ii) Assign x_1 to x^* and $f(x_1)$ to $f(x^*)$. The sign * denotes the best solution identified so far;

iii) Step n=1, 2,…, n. x_n denotes the current solution at iteration n. Obtain a new solution x in the neighborhood of x_n using a sampling process;

iv) Testing:

a. if $f(x) \le f(x_n)$, assign x to x_{n+1};

if $f(x) \le f(x^*)$, assign x to x^* and $f(x)$ to $f(x^*)$;

b. else

get a random number p in $[0.0;1.0]$;

evaluate the probability of accepting worse solutions at iteration n, p(n) by (1) where K is the Boltzman constant.

$$p(n) = e^{\frac{f(x_n) - f(x)}{K \cdot \text{Temperature}}} \quad (1)$$

if $p \le p(n)$ then assign x to x_{n+1};

v) End if a stopping rule is reached. Otherwise go to iii).

Simulated Annealing has an analogy with the cooling process of a thermodynamic system, TDS. In this analogy, a state of a TDS is equivalent to the solutions of a CP. The energy of a TDS corresponds to the evaluation function, f, of the CP and the temperature of a TDS corresponds to the control parameter of the CP problem. As in TDS systems, the Temperature should be cooled in a slow way. This enables sub-systems to reorganize themselves so that a low energy system is built. The temperature parameter T is usually lowered by steps. In each step the algorithm performs a maximum number of iterations. Once this maximum is reached, the current temperature is lowered by a cooling parameter α, in $[0.0;1.0]$. This means that at the beginning, the probability of accepting worse solutions (1), is larger turning more probable the acceptance of worse solutions and making the search more chaotic. As the process goes on and the temperature lowered, it gets more difficult to accept worse solutions meaning that the search is being conducted in a promising area from where one doesn't want to leave. The Simulated Annealing algorithm proceeds from one solution x to another one in its neighbourhood, N(x). The structure of N(x) is quite simple to define in discrete problems, as expansion planning ones. One departs from an initial solution and simply samples possible equipments to add to the system or to eliminate from the current solution. Finally, the search procedure ends if a stopping rule is achieved. This can correspond to the absence of improvements in a pre-specified number of iterations, to perform a maximum number of iterations or to lower the temperature till a minimum level.

III. MATHEMATICAL FORMULATION

A. *Short Term Analysis*

The operation cost can be evaluated using a DC based model (2-6).

$$\min OC = \sum c_k . Pg_k + G.\sum PNS_k \quad (2)$$

$$\text{subj} \quad \sum Pg_k + \sum PNS_k = \sum Pl_k \quad (3)$$

$$Pg_k^{min} \le Pg_k \le Pg_k^{max} \quad (4)$$

$$PNS_k \le Pl_k \quad (5)$$

$$P_b^{min} \le \sum a_{bk} . (Pg_k + PNS_k - Pl_k) \le P_b^{max} \quad (6)$$

In this model, c_k, Pg_k, Pl_k and G are the variable generation cost, the generation and the load connected to bus k and a penalty specified for the Power Not Supplied. Pg_k^{min} and Pg_k^{max} are the generation limits in node k, P_b^{min} and P_b^{max} are the limits of the active flow in branch b and a_{bk} is the sensitivity coefficient of the active flow in branch b regarding the injected power in node k.

One can include an estimate of branch active losses by running a first dispatch problem as (2) to (6) and then obtaining voltage phases so that the active losses in branch ij are approximated by (7). In this expression, g_{ij} is the branch conductance and θ_{ij} is the phase difference across the branch. Once this estimate is obtained, loads are altered by adding to each of them half of the losses of the branches connected to each node. This change on the load vector requires an adjustment of the generation vector by running again the dispatch problem. This defines an iterative problem that ends as soon as the phase in each bus in two successive iterations gets smaller than a threshold.

$$Loss_{ij} \approx 2.g_{ij}.(1 - \cos\theta_{ij}) \quad (7)$$

B. *Long Term Analysis*

According to the ideas in [6,7], the transmission expansion problem includes the following four criteria:

- Operation Costs, OC, given by the sum of the cost of the dispatch problem (2-6) for each period p of the horizon, OC_p, referred to initial period using a return rate r. Admitting that the planning horizon is discretized in np periods, OC is given by (8);

$$OC = \sum_{p=0}^{np-1} \frac{OC_p}{(1+r)^p} \quad (8)$$

- Investment Costs, IC, given by the sum of the investment costs in each of the np periods using an expression similar to (8). In each period IC_p results from the expansions selected for that period;
- Expected Value of the Non Supplied Energy, EENS, in order to characterize the expansion plan from the point of view of the quality of service. The evaluation of EENS is detailed in Section IV;
- Exposure Index, Iexp, in order to evaluate the risk of the expansion plan regarding load uncertainties. These uncertainties are modelled by trapezoidal fuzzy numbers according to ideas in Section IV.

C. *Mathematical Formulation*

The transmission expansion problem is a multicriteria problem formulated by (9) to (13). In this formulation f is the vector of criteria, X is the discrete list of possible investments and Y represents operation variables as voltage phases, generations and active flows. Expressions (10) are operation constraints for each period of the horizon and (11) are constraints related for instance to limits on the investment in terms of their value or number specified either per period of the horizon or for the entire planning horizon.

$$\min f = [OC, IC, EENS, I\exp] \quad (9)$$

$$\text{subj} \quad A.X + B.Y \le d \quad (10)$$

$$C.X \le c \quad (11)$$

$$\text{limits on } Y \quad (12)$$

$$X \in \{x_1, x_2, ..., x_n\} \quad (13)$$

IV. SOLUTION ALGORITHM

A. Dealing with the Reliability of Components

The quality of service of the transmission grid was evaluated computing an estimate of the Expected Energy Non Supplied, EENS. This estimate can be obtained by running for each period of the planning horizon a Monte Carlo Simulation. This method has a number of different approaches to perform the sampling of system states to analyse. Non-chronological sample strategies are based on Forced Outage Rates of components to identify states in a non-chronological sequence. In this case, it is possible to evaluate an estimate of the expected value of the Power Not Supplied, PNS. Chronological samples require the use of both Forced Outage Rates and Repair Rates so that for each state it is also sample its duration. In this case, it is possible to obtain an estimate of the Expected Energy Non Supplied, EENS. The price to pay is a much larger computation time of the simulation. References [8] describe a pseudo-chronological sampling strategy based on a traditional non-chronological one. As the sampling procedure evolves, once a failure state is identified they are performed backward and forward sampling till previous and a next success states are obtained. This approach still allows one to estimate the Expected Energy Non Supplied, EENS, with the advantage of a much reduced computational time when compared with a pure chronological sampling.

B. Dealing with the Uncertainties on the Load Evolution

Fuzzy sets emerged in the 1960's and can be considered an extension of Boolean sets since they admit an infinite number of membership degrees of an element x to Ã. In normalized fuzzy sets the elements of the universe X are mapped by a membership function $\mu(x)$ in [0.0;1.0] leading to a set of ordered pairs as in (14).

$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x)), x \in X\} \quad (14)$$

A fuzzy number is a special class of fuzzy sets in which the membership function is convex and piecewise continuous. In Figure 1 we represent a trapezoidal fuzzy number that can be used, for instance, to translate a proposition like "*The load in bus k is most likely in [a2;a3] but values in [a1;a2[and in]a3;a4] should not be discarded*". Fuzzy sets in general, and trapezoidal numbers in particular, can be used to deal with incomplete information or with the inherent subjectivity that is present in numerous human language expressions.

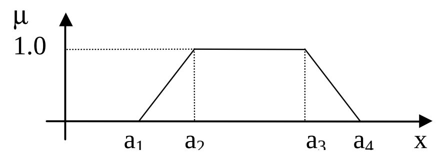

Figure 1. Trapezoidal fuzzy number.

During the 90[th] several models were developed to incorporate load uncertainties represented by trapezoidal fuzzy numbers in power flow studies. In this scope, references [9, 10, 11] describe an AC Fuzzy Power Flow Model, a DC Fuzzy Optimal Power Flow Model and a model to evaluate the impact of load uncertainties in nodal short-term marginal prices. Reference [10] details a model to build the membership functions of optimal generations, active branch flows and phases. If necessary, it also leads to the membership function of Power Not Supplied, PNS, in the sense that the system has no capacity to accommodate load uncertainties below an uncertainty level α. This value is determined by insufficient generation capacity, by bottlenecks in the transmission system or by situations where there are simultaneously problems at these two levels. Figure 2 illustrates a membership function obtained for PNS. Above level α the Power Not Supplied is zero indicating there is enough generation and transmission capacity to accommodate load uncertainties. Below α, PNS is not zero meaning that the system is exposed to load uncertainties till level α. This means the Exposure Index corresponds to the highest α for which the Power Not Supplied is not zero.

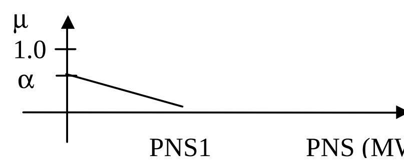

Figure 2 – Membership function of Power Not Supplied.

Using these ideas, the DC Fuzzy Optimal Power Flow is run for each period p in the planning horizon admitting that loads are represented by trapezoidal fuzzy numbers. This leads to the Exposure Index per period p, $I_{exp,p}$. In an aggregated way for the entire horizon an expansion plan can be characterized by the arithmetic mean of the values per period (15) or, in a more conservative way, by the maximum of the values per period, as in (16).

$$I_{exp} = \frac{1}{np} . \sum_{p=1}^{np} I_{exp,p} \quad (15)$$

$$I_{exp} = \max(I_{exp,p}; p = 1...np) \quad (16)$$

C. Addressing the Multicriteria Problem

The multicriteria problem (9) to (13) can be addressed by aggregating all criteria in a single function reflecting the importance that the Decision Maker, DM, gives to each criteria. This requires the definition a priori of these weights so that the search procedure gets in fact immediately directed. Other approaches aim at identifying the non dominated border of the solution space to be presented to the Decision Maker.

The DM can then conduct a *Trade-Off* analysis, for instance, to get more complete information.

Instead of any of these approaches and considering the complexity of the problem under analysis, the developed application starts by identifying a first non dominated solution using the ε-*constrained method* [12]. This method requires that all criteria in (9-13), except one, is converted into constraints by specifying aspiration levels. In our case, the DM specifies aspiration levels for the Investment Cost, for EENS and for Iexp so that we get an auxiliary single objective problem to minimize Operation Cost. This non dominated solution is then presented to the DM. If he is not satisfied, he modifies the aspiration levels and solves the single objective problem again.

D. Solving the Auxiliary Single Objective Problem

The auxiliary single objective problem still retains much of its complexity given its discrete and combinatorial nature. This is addressed by providing a list of possible expansions and reinforcements to be used to obtain a consistent and global plan. This means that the plan should not correspond to a sequence of yearly plans built in successive and independent way. Apart from this, if an installation is built in a period p, then it will be available on the next periods. Conversely, if it is removed from the current solution in period p, then it will also be eliminated from all subsequent periods. The solution gets more realistic by imposing limits on the number of installations to be built per period or to the number of installations to be built in the whole horizon, reflecting financial constraints. These constraints can be also be formulated by directly imposing limits on the yearly or global investments instead of limits on their number.

The next algorithm details the application of Simulated Annealing to the transmission expansion-planning problem:

i) Consider the current transmission/generation system as the initial topology and denote it as x^o;

ii) Analyze the current solution:
   a. solve an optimization problem according to (2) to (6) to evaluate the short-term operation costs, OC, related with the current topology;
   b. compute the IC, Iexp and EENS and the Evaluation Function, EF, by (17);

$$EF^o = OC^o + Pen_1.IC^o + Pen_2.Iexp^o + Pen_3.EENS^o \qquad (17)$$

   c. assign EF^o to EF^{opt} and to $EF^{current}$;
   d. assign x^o to x^{opt} and to $x^{current}$;
   e. set the iteration counter, ic, to 1;
   f. set the worse solution counter, wsc, at 0;

iii) Identify a new plan, selected in the neighborhood of the current one by sampling one of the periods, and then sampling a new installation to build, among the ones in the list of possible additions, or to decommission, among the existing ones. This plan is denoted as x^{new};

iv) Analyze the new plan:
   a. check if the number of installations to build per period exceeds the specified limit. If it does, discard this solution and return to iii);
   b. compute OC^{new}, IC^{new}, $Iexp^{new}$, $EENS^{new}$ and EF^{new};

v) If $EF^{new} < EF^{opt}$ then
   a. assign EF^{new} to EF^{opt} and to $EF^{current}$;
   b. assign x^{new} to x^{opt} and to $x^{current}$;
   c. set the worse solution counter, wsc, at 0;

vi) If $EF^{new} \geq EF^{opt}$ then
   a. get a random number $p \in [0{,}0;1{,}0]$;
   b. compute the probability of accepting worse solutions $p(x^{new})$ by (18);

$$p(x^{new}) = e^{\frac{EF^{current} - EF^{new}}{K.T}} \qquad (18)$$

   c. if $p \leq p(x^{new})$ then assign x^{new} to $x^{current}$ and EF^{new} to $EF^{current}$;
   d. increase the worse solution counter, wsc, by 1;

vii) If wsc is larger than a specified maximum number of iterations without improvements than go to ix);

viii) If the iteration counter ic is larger than the maximum number of iterations per temperature level then:
   a. decrease the temperature T by α smaller then 1.0;
   b. if the new temperature is smaller then the minimum allowed temperature then go to ix);
   c. set the iteration counter ic to 1;
   Else, increase the iteration counter ic by 1;
   Go back to iii);

ix) End.

V. Nodal Marginal Prices And Marginal Remuneration

The marginal price of electricity in node k at instant t is defined as variation of the objective function of the optimization function regarding a variation of the load in that bus at that instant [13, 14]. This corresponds to expression (19).

$$\rho_k(t) = \frac{\partial f(t)}{\partial Pl_k(t)} \qquad (19)$$

These prices typically display a geographical dispersion given the distribution of generation and loads along the network, the limits of branch flows and the losses. Apart from that, they can be computed in terms of two time scales. Short-Term Marginal Prices, STMP, reflect operation costs and are easily computed as sub-products of the solution of an optimization problem. In particular, for a linearized formulation as the dispatch problem (2) to (6), nodal marginal prices for a given instant in which there is a set of nodal load values are related with the values of the dual variables when the optimum is reached. For this dispatch problem, the short term marginal price is given by (20).

$$\rho_{ik} = \gamma_i + \gamma_i . \frac{\partial Loss}{\partial Pl_{ik}} - \sum \mu_{i,mn} . \frac{\partial P_{i,mn}}{\partial Pl_{ik}} + \sigma_{ik} \qquad (20)$$

In this expression, γ_i is the dual variable of constraint (3), Loss represents the active losses in all system branches, $\mu_{i,mn}$ is the dual variable of branch flow limit constraints (6) and σ_{ik} is the dual variable of constraint (5) related with node k. Typically, STMP are very volatile since they depend on the load level, on the distribution of loads along the system, on generator or branch outages and on generation costs. However, they are used in several countries to define a term of the tariffs for use of the networks.

When computing STMP the components of the network are considered fixed. Differently, if the time horizon is longer and one admits expansions or reinforcements, then the objective function can incorporate not only an estimate of operation costs along the planning horizon but also investment costs. In this case, we are interested in long-term marginal prices, LTMP. These prices are much more complex to compute since investments have to be decided in the scope of a transmission expansion planning problem. Reference [15] details the computation of Investment Cost Related Prices, ICRP, used in England & Wales to determine transmission use of network tariffs as an approximation to LTMP.

LTMP can no longer be defined by an expression as (19) given that transmission expansion problems are discrete. This means that an incremental type expression as (21) is more adequate. In (21) ΔCO and ΔCI represent the variation of operation and investment costs if there is a variation ΔPl_k of the load connected to node k. Given this definition, these prices are possibly more correctly named as Long Term Incremental Prices [16].

$$LTMP_k = \frac{\Delta CO}{\Delta Pl_k} + \frac{\Delta CI}{\Delta Pl_k} \qquad (21)$$

The computation of the Marginal Based Remuneration, MBR, assumes that each load pays and each generator is paid the electricity at the nodal price at the node they are connected to. If T_p is the duration of period p, $LTMP_{pk}$, Pl_{pk} and Pg_{pk} are the LTMP, the load and the generation in node k in period p, np is the number of periods and nnodes is the number of nodes, then MBR is given by (22).

$$MBR = \sum_{p=1}^{np} T_p \sum_{k=1}^{nnodes} LTMP_{pk}.(Pl_{pk} - Pg_{pk})\ € \qquad (22)$$

VI. Case Study

A. *Portuguese 400/220/150 kV Transmission Network*

The described algorithm was used to build a 6-year expansion plan for the Portuguese National Transmission System [17]. Portuguese regulations require that the TSO submit to the Regulatory Agency, ERSE, such plan and the first one was prepared for 2002-2007. It was admitted a yearly load increase of 3,5%, a return rate of 10%, a maximum number of 36 investments per year and a number of new power stations to be commissioned (4 combined cycles of 392 MW each in 2002, 2004, 2005 and 2006 and two hydros with 236 and 178 MW in 2002 and 2004).

B. *List of Possible Investments*

The Planner specifies a list of possible expansions that can be implemented along the planning horizon. Table 1 presents part of the list specified for this case study. For each element in this list, they are indicated the extreme nodes of the equipment, its type (overhead line or transformer and the corresponding voltage), the rated power and the investment cost in million Euro. The complete list includes 180 possible investments. It should be said that it is possible to duplicate lines or transformers between the same extreme nodes, thus increasing the combinatorial nature of the problem.

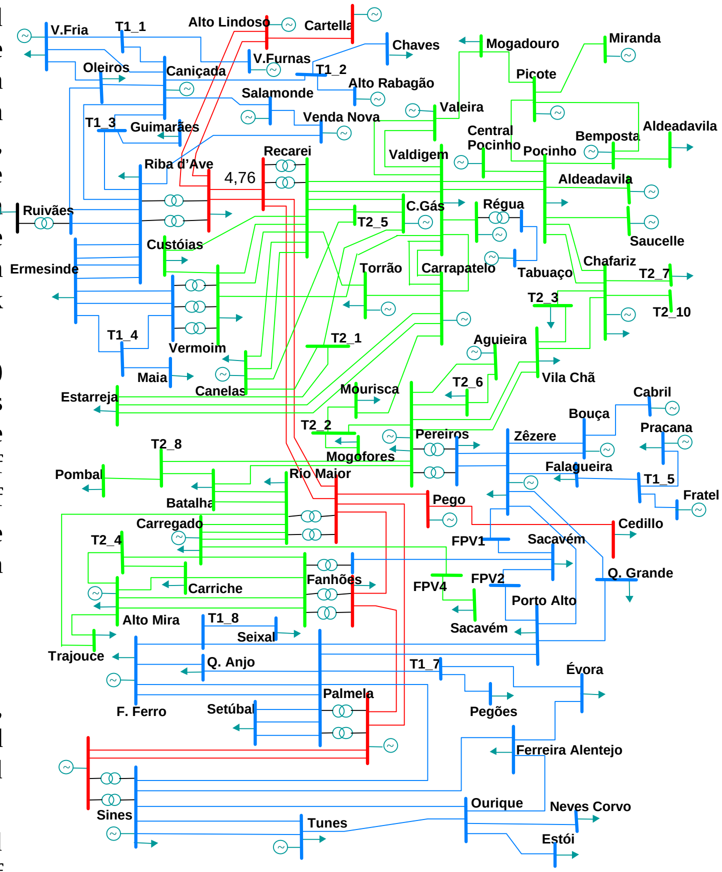

Figure 3 – The 400/220/150 kV Portuguese transmission network in 2002.

C. *Expansion Plan for 2002-2007*

The proposed algorithm selected a plan that includes 100 investments distributed as follows: 36 in 2002, 12 in 2003, 27 in 2004, 14 in 2005, 7 in 2006 and 4 in 2007. Table 2 gives information about the distribution of the investments detailed in Table 1 along the planning horizon.

D. *Long Term Marginal Prices*

Once the most adequate expansion plan was identified, long-term nodal marginal prices were computed for each year of the horizon. Table 3 shows these prices for some of the nodes. As a result of the expansion, the network will have 208 nodes by 2007 compared with 159 in 2001.

E. *Characterization of the Adopted Solution*

Table 4 presents results to characterize in a more complete way the selected expansion plan. For each year this table includes the EENS in GW.h and in % of the demand, the value of Iexp, the long term marginal remuneration (YLTMR), the operation costs (YOC), the investment costs (YIC) and the total costs (YTC). The mentioned Table also includes the global values for the total costs (TC) and for the long-term marginal remuneration (LTMR) as the sum of the yearly values adjusted by the return rate referred in Section III.B. This Table also presents the percentage of the total costs recovered by the long term marginal remuneration, LTMR.

Table 1 – Partial list of possible investments.

No.	Extreme nodes		Type (kV)	$P_{ij}^{máx}$ (MW)	CI (x10^6€)
1	167	10	Line 400	1480,0	11,778
2	49	31	Line 220	344,0	15,313
3	28	164	Line 150	234,0	1,99335
4	186	108	Line 150	277,0	1,6401
5	1	191	Line 400	1386,0	5,208
6	192	31	Line 220	344,0	3,63
7	102	189	Line 150	104,0	0,42
8	68	207	Line 220	377,0	2,16255
9	28	202	Line 150	234,0	6,9745
10	213	8	Line 400	1480,0	5,09935
11	210	79	Line 220	688,0	2,90475
12	214	169	Line 150	554,0	3,90085
13	217	171	Line 220	344,0	3,8102
14	106	107	Trf. 150/60	170,0	5,38275
15	175	35	Trf. 400/60	170,0	3,2184
16	171	190	Trf. 220/60	126,0	6,1522
17	169	187	Trf. 150/60	170,0	9,2306
18	167	200	Trf. 400/60	170,0	3,817
19	188	201	Trf. 400/60	170,0	5,2
20	112	213	Autotrf. 400/150	450,0	5,0
21	210	211	Trf. 220/60	126,0	6,1522
22	217	218	Trf. 220/60	126,0	7,2136
23	215	216	Trf. 220/60	126,0	4,1246

Table 2 – Partial list of the selected investments.

2002	2003	2004	2005	2006	2007
1	4	5	8	11	13
3		16	9	12	22
14		17	14	20	23
15			18	21	
15			19		

Table 3 – Long Term Marginal Prices (€/kWh).

node	2002	2003	2004	2005	2006	2007
Alto Lindoso	0.0366	0.0339	0.0296	0.0275	0.0240	0.0233
Riba de Ave 1	0.0369	0.0341	0.0300	0.0279	0.0243	0.0237
Riba de Ave 2	0.0368	0.0341	0.0299	0.0278	0.0242	0.0236
Riba de Ave 3	0.0371	0.0344	0.0302	0.0281	0.0245	0.0238
Setúbal 1	0.0374	0.0342	0.0306	0.0280	0.0246	0.0368
Setúbal 2	0.0376	0.0343	0.0308	0.0282	0.0247	0.0370
Palmela 1	0.0371	0.0340	0.0305	0.0279	0.0222	0.0202
Palmela 2	0.0373	0.0341	0.0305	0.0279	0.0245	0.0367
Sines 1	0.0366	0.0336	0.0301	0.0276	0.0221	0.0213
Sines 2	0.0365	0.0334	0.0301	0.0276	0.0224	0.0228
Sines 3	0.0366	0.0335	0.0301	0.0277	0.0224	0.0229
Mortágua	0.0382	0.0355	0.0315	0.0292	0.0257	0.0250
Pego	0.0372	0.0343	0.0306	0.0281	0.0240	0.0230
Fanhões 1	0.0382	0.0349	0.0312	0.0284	0.0224	0.0222
Fanhões 2	0.0385	0.0351	0.0315	0.0286	0.0261	0.0234
Fanhões 3	0.0390	0.0356	0.0318	0.0289	0.0260	0.0274
Fanhões 4	0.0383	0.0350	0.0312	0.0284	0.0224	0.0222
Cedillo	0.0423	0.0384	0.0345	0.0322	0.0287	0.0291
Rio Maior 1	0.0378	0.0348	0.0310	0.0285	0.0244	0.0234

The values in Table 4 deserve some comments:

- in the first place, it should be noticed that EENS remains very reduced along the whole horizon namely when compared with the demand. Its percentage increases to the end of the horizon certainly reflecting less investments in the final years;
- the exposure index has a similar evolution. In any case, if the load evolution is confirmed in the first years of the horizon, the plan can always be adapted to include more investments in the final years since Portuguese regulations impose that it is updated every two years;

the percentage of cost recovery, 99,45%, virtually ensures the full recovery of regulated costs and should be compared with very small percentages (between 10 and 20%) referred in the literature if short-term marginal prices were used.

Table 4 – Values for the criteria and remunerations.

	2002	2003	2004	2005	2006	2007
EENS (GW.h)	8,51	13,72	12,33	17,64	24,12	31,59
EENS/demand(%)	0,02	0,03	0,03	0,04	0,05	0,06
Iexp	0,0	0,0	0,188	0,0	0,286	1,0
YLTMR (10^6 €)	117,9	96,4	104,2	94,3	143,6	247,5
YOC(10^6 €)	46,1	44,6	42,6	44,9	114,1	39,6
YIC (10^6 €)	212,7	45,8	113,1	58,8	29,8	16,5
YTC (10^6 €)	258,7	90,4	155,8	103,6	143,8	56,1
TC (10^6 €)	808,36					
TLTMR (10^6€)	803,93					
TLTMP/TC (%)	99,45					

VII. Conclusions

This paper describes an approach to the transmission expansion planning problem addressing a number of crucial issues in order to turn it more realistic. In this way, the formulation and the adopted solution algorithm retains the discrete multiyear and dynamic nature of the problem, it considers a four criteria and it adequately considers uncertainties using fuzzy and probabilistic models. This holistic view over this problem is crucial from several points of view. It is important in the sense that an expansion plan has a multiyear nature meaning that it does nor correspond to a concatenation of yearly plans built in a sequential way. It also means that investments are not selected only because they respond to a local bottleneck. In fact, it is frequent that an investment aiming at solving a particular problem in a geographic location in a particular year can also eliminate problems in subsequent years or in other locations given the meshed nature of transmission networks. Finally, this approach also leads to the computation of long term marginal prices that display very good properties in terms of their more reduced volatility when compared with short term ones and it leads to an almost complete recovery of regulated costs. The percentage obtained for the Portuguese Transmission Network for the period 2002-2007, 99,45%, clearly illustrates the potential of this approach.

VIII. References

[1] F. Schweppe, M. Caramanis, R. Tabors, R. Bohn, Spot Pricing of Electricity, London, Kluwer Academic Publishers, 1988.

[2] I. J. Pérez-Arriaga, F. Rubio, J. Puerta, J. Arceluz, J. Marin, “Marginal Pricing of Transmission Services: An Analysis of Cost Recovery”, IEEE Trans. on Power Systems, vol. 10, no. 1, February 1995.

[3] J. T. Saraiva, J. P. Silva, M. T. Ponce de Leão, “Evaluation of the Marginal Based Remuneration - A Case Study Using the Portuguese Transmission Network”, Proceedings of the 2001 IEEE Porto Power Tech, Porto, Portugal, September 2001.

[4] S. Kirkpatrick, C. D. Gelatt, M. P. Vecchi, “Optimization by Simulated Annealing”, Science, vol. 220, no. 4598, 1983.

[5] E. Aarts, J. Korst, Simulated Annealing and Boltzman Machines, New York, John Wiley & Sons, 1990.

[6] A.S.D. Braga, J. T. Saraiva, “Transmission Expansion Planning and Long Term Marginal Prices Calculation Using Simulated Annealing”, Proceedings of the Bologna Power Tech, BPT’03, Bologna, June 2003.

[7] A. S. Braga, J. T. Saraiva, “From Short to Long Term Marginal Prices – Advantages and Drawbacks”, Proceedings of the Med Power 2002, Athens, Greece, November 2002.

[8] A. Leite da Silva, L. A. Manso, J. C. Mello, R. Billinton, “Pseudo-Chronological Simulation for Composite Reliability Analysis with Time Varying Loads”, IEEE Trans. on Power Systems, vol. 15, no. 1, February 2000.

[9] V. Miranda, M. A. Matos and J. T. Saraiva, "Fuzzy Load Flow - New Algorithms Incorporating Uncertain Generation and Load Representation", in Proceedings of the 10th PSCC, Butterworths, London, 1990.

[10] J. T. Saraiva, V. Miranda and L.M.V.G. Pinto, "Impact on Some Planning Decisions from a Fuzzy Modelling of Power Systems", IEEE Trans. Power Systems, vol. 9, no. 2, May 1994.

[11] J. T. Saraiva, “Evaluation of the Impact of Load Uncertainties in Spot Prices Using Fuzzy Set Models”, 13th Power Systems Computation Conference, PSCC’99, Trondheim, Norway, July 1999.

[12] C.-L. Hwang, A.S.Masud, Multiple Objective Decision Making – Methods and Applications, Lecture Notes in Economics and Mathematical Systems, Springer-Verlag, Berlin, 1979.

[13] M. Rivier, I. J. Pérez-Arriaga, “Computation and Decomposition of Spot Prices for Transmission Pricing”, 11th Power Systems Computation Conference, PSCC’93, Avignon, France, August 1993.

[14] H. Rudnick, R. Palma, H. Lira, “Penalty Factor Calculations for Marginal Pricing of Transmission Systems in a Hydroelectrical System”, Proceedings of the Stockholm Power Tech, SPT’95, Stockholm, Sweden, June 1995.

[15] M. C. Calviou, R. M. Dunnett, P. H. Plumptre, “Charging for Use of a Transmission System by Marginal Cost Methods”, 11th Power Systems Computation Conference, PSCC’93, Avignon, August 1993.

[16] E. Khan, Electric Utility Planning and Regulation, American Council for an Energy-Efficiency Economy, Washington DC, USA, 1988.

[17] Rede Eléctrica Nacional, REN, Characterization of the National Transmission Grid in December 31st 2001”, (in Portuguese), March 2002, available in http://www.ren.pt.

IX. BIOGRAPHIES

António Silvestre Braga was born in Seia, Portugal, in 1964. He received his licentiate and MSc degrees from Faculdade de Engenharia da Univ. do Porto (FEUP) in 1991 and 1997, in Electrical and Computers Engineering. In 1991 he joined the Polytechnic Institute of Guarda (IPG). He completed his PhD in 2004 in Electrical and Computer Engineering at FEUP with a thesis on transmission expansion planning and the computation of long-term nodal marginal prices.

João Tomé Saraiva was born in Porto, Portugal in 1962. In 1987, 1993 and 2002 he got his MSc, PhD, and Agregado degrees in Electrical and Computer Engineering from the Faculdade de Engenharia da Universidade do Porto, FEUP, where he is currently Professor. In 1985 he joined INESC Porto – a private research institute – where he was head researcher or collaborated in several projects related with the development of DMS systems, quality in power systems, and tariffs due for the use of transmission and distribution networks. Several of these projects were developed under consultancy contracts with the Portuguese Electricity Regulatory Agency.