TRANSMISSION EXPANSION PLANNING AND LONG TERM MARGINAL PRICES CALCULATION USING SIMULATED ANNEALING

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***Abstract* — This paper addresses the problem of transmission expansion-planning in the context of the re-regulation and liberalization of power systems. The transmission expansion-planning problem is formulated as an integer problem and it is solved keeping that characteristic using Simulated Annealing. In the scope of the access to the transmission networks and the corresponding payments for Use of Networks, the paper discusses the advantages and drawbacks from adopting several cost methods and, more specifically, short-term and long-term nodal marginal prices. Long-term marginal prices are computed in the framework of the Simulated Annealing algorithm and led to the calculation of the Marginal Based Remuneration to the transmission company. The paper includes case studies based on the Portuguese 400/220/150 kV network and on a didactic 6-bus system.**

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

I. INTRODUCTION

The electric industry is going through a process of transformation and liberalization that poses several challenges at different levels. The implementation of market mechanisms lead in a first place to the creation of wholesale electricity markets with pool mechanisms or bilateral transactions. The transmission network corresponds to an independent entity that must provide the transmission service in a transparent way and that must be remunerated for it. The operation of the system is coordinated by the Independent System Operator - ISO - or, in same cases, by a Transmission System Operator – TSO. TSO's result from merging a transmission provider with an ISO. In several countries, as in the USA, the operation of several transmission companies has also been reorganized in a coordinated way leading to Regional Transmission Organizations, RTO.

At the supply level the change is more recent and is leading to the separation between distribution network providers and retailing entities. With this separation, the situation of network companies – at the transmission or distribution levels – gets conceptually similar. They act on a monopoly basis and must be regulated [1] to remunerate them by Tariffs for Use of Networks and to ensure their service is fair and transparent.

The literature describes a large number of approaches to compute Tariffs for Use of Networks [2, 3, 4, 5]. Each method typically has some advantages and disadvantages considering their technical robustness, implementation easiness, fairness, transparency, ability to transmit economic signals in the short or in the long run and possible application in anonymous pool markets. Among them, marginal based methods are particularly interesting given their technical robustness and the possibility to achieve efficient cost allocation strategies in the short or in the long term.

The horizon under analysis is related with the costs included in the problem leading to the computation of short-term nodal prices [6, 7, 8] or long-term ones. Short-term marginal prices are easily computed as by-products of dispatch problems but they have drawbacks [8, 9] given their volatility and dependence on the load level and on the components in service. The related Marginal Based Remuneration is usually small when compared with the regulated costs [5, 10], given that investment costs are not considered in the evaluation of short-term marginal prices.

Long-term marginal prices have the potential to successfully address several of these drawbacks. They reflect long-term investment costs as well as short-term operation costs, they are less volatile and they lead to a reduction of the Revenue Reconciliation Problem, due to the smaller difference between the regulated remuneration and the long-term Marginal Based Remuneration. Given these interesting properties, we presented a first model in [11] aiming at computing long-term marginal prices in the scope of a transmission expansion-planning problem. In this paper that model is enhanced namely considering a multi-period approach that turns the whole planning process more realistic. The model is able to compute long-term marginal prices in each node for each planning period as well as the corresponding long term marginal based remuneration.

The paper is organized as follows. After this introductory section, Section II presents an overview about Simulated Annealing, Section III details the mathematical formulation of the expansion-planning problem and Section IV addresses the application of Simulated Annealing to this particular problem. Section V describes the computation of both short term and long-term nodal marginal prices and the corresponding marginal remuneration and Section VI includes two case studies. One of them is based in a set of realistic simulations

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on the 400/220/150 kV Portuguese transmission grid and the second one adopts a small 6-bus system already used in the literature [10]. Finally, Section VII draws the most relevant conclusions and indicates directions of future research.

II. SIMULATED ANNEALING – AN OVERVIEW

In the last decade, several optimization techniques emerged both in conceptual terms and in current applications. These techniques, often called meta-heuristics, include Tabu Search, Neural Networks, Simulated Annealing, Genetic Algorithms and its development to Genetic Programming, Literature includes nowadays a large number of papers reporting applications of these techniques to several problems showing their success and their special ability to address problems having some particular characteristics.

In particular Simulated Annealing and Genetic Algorithms are used to address combinatorial problems due to the presence of discrete variables. Traditionally, this type of problems could be 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. As it is easily understood, this does not ensure that the selected integer solution corresponds to the optimal one. Other approaches adopted branch-and-bound based techniques, usually leading to a large amount of computation time.

However, there are two aspects that must be referred:

- several continuous optimization algorithms – as gradient based techniques – have the conceptual problem of eventually converging to local optima as illustrated in Figure 1. Gradient-based approaches can converge to solution A and the iterative process will be trapped there since derivatives are zero. Apart from that, the final solution can vary depending on initialization conditions;
- secondly, in several real life problems, decision makers are not really interested in the global optimum. They are, in fact, interested in a good or adequate solution, for which some quality index is evaluated. The process would end if an improvement, although not impossible to obtain, can lead to a large computational time.

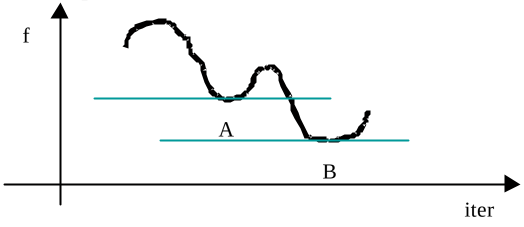

Fig. 1. Illustration of an optimization process with local optima.

Simulated Annealing was developed by Kirkpatrick et al [12] based on the Metropolis algorithm dated from 1953. It is a search procedure in which it is included the possibility of eventually accepting a solution that is worse than the current one. The basic idea corresponds to start at an initial solution, x_1, evaluate that solution using an evaluation function, $f(x_1)$, and sample a new solution in the neighborhood of x_1. If this new solution improves $f(x_1)$, then it is accepted. If it is worse than the current one, it can still be accepted depending on a so-called probability of accepting worse solutions. This mechanism eventually allows the iterative process to escape from a local optimum, as A in Figure 1, and go on iterating towards B. In a more formal way, the algorithm can be summarized as indicated in the next paragraphs.

<u>Simulated Annealing Basic Algorithm</u>

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 until this step;

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 $f(x) \le f(x_n)$ then assign x to x_{n+1};
    if $f(x) \le f(x^*)$ then
      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

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

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

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

In expression (1), K is the Boltzman constant. Regarding this algorithm there are some issues to be clarified:

- in the first place, the solution of a combinatorial problem, CP, has a clear analogy with the cooling process of a thermodynamic system, TDS. In this analogy, a state of a TDS is equivalent to the solutions or combinations 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;
- secondly, a TDS system should be cooled in a slow way. This enables sub-systems to reorganize themselves so that a low energy system is built. In this sense, the temperature of the CP must be lowered in a sufficiently slow way in order to identify a good quality solution;
- thirdly, 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 $[0.0;1.0]$. Therefore, at the beginning of the search procedure, the probability of accepting

worse solutions p(n), given by (1), is larger. This turns it more probable to accept worse solutions making the search more chaotic in the sense that larger areas of the solution space are more likely to be investigated. As the process goes on, the temperature is lowered, turning it more difficult to accept worse solutions. This means that the search is eventually being conducted in a promising area that one doesn't want to leave;

- fourthly, the Simulated Annealing algorithm proceeds from one solution x to another one in its neighbourhood. The definition of the neighbourhood of x, N(x), is a strategic aspect of the algorithm in the sense it has an impact on the design of the final solution. 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. Another example corresponds to the application of Simulated Annealing to minimize transmission losses in a network by changing taps of transformers or capacitor banks. Departing from the nominal positions, one can simply sample a transformer or capacitor, and then sample if the tap goes upwards or downwards by one step. This leads to a neighbour solution regarding the current one;
- 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 parameter till a minimum level.

III. MATHEMATICAL FORMULATION

The DC OPF problem used to calculate the operation costs for a given topology is formulated according to (2) to (7). In this formulation c_k, Pg_k and Pl_k are the variable generation costs, the generation and the load connected to node k, G is the penalty factor assigned to Power Not Supplied, PNS, a_{bk} is the sensitivity coefficient of the active power flow in branch b regarding the injected power in node k, Pg_k^{min} and Pg_k^{max} are the minimum and maximum generations of the generator in node k and P_b^{min} and P_b^{max} are the minimum and maximum values of the active power flow in branch b.

$$\min OC = \sum c_k . Pg_k + G . \sum PNS_k \tag{2}$$

$$\sum Pg_k + \sum PNS_k = \sum Pl_k \tag{3}$$

$$Pg_k^{min} \le Pg_k \le Pg_k^{max} \tag{4}$$

$$PNS_k \le Pl_k \tag{5}$$

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

$$\sum a_{bk} . \left(Pg_k + PNS_k - Pl_k\right) \ge P_b^{min} \tag{7}$$

This model can be enhanced according to [7, 8] in order to include an estimate of branch active losses. This estimate is computed adopting an iterative process that starts by solving an initial problem using (2) to (7). At the end of it, one calculates voltage phases and an estimate of active losses in each branch. Active losses are then allocated to the loads in the extreme nodes of each branch. The change in the load pattern requires solving a new dispatch problem. This leads to an iterative process that converges when the voltage phases in all buses in two successive iterations are close enough.

The expansion planning problem is formulated considering that one wants to minimize total costs, TC, resulting from operation costs, OC_i, plus investment costs, IC_i, in each period i of the planning horizon (8).

$$TC = \sum_{\text{all periods}} \left(OC_i + IC_i\right) \tag{8}$$

The investments are selected among a list of possible installations to build – lines and substations in a way that the dynamic nature of the problem is captured. To achieve this the planning horizon is discretized in a number of periods. For each of them it is specified the forecasted load evolution and the solution algorithm builds expansion plans by sampling new installations to build or existing installations to decommission along the horizon. The consistency of a plan and the global nature of the evaluation process are ensured by considering:

- if a new installation is sampled to be built in a particular year, then it will be available in all subsequent periods;
- in a similar way, if an existing installation is sampled to be decommissioned, then it will not be available in the following periods;
- therefore, for a particular year, an expansion plan can integrate installations to be built, to be decommissioned or the available equipments can simply be the same as in the previous period;
- in order to turn the model more realistic, one can impose limits on the number of new installations to be built per period, as a way to reflect financial constraints. This means that, after a new sampling, the number of installations per year is updated and it is compared with the specified limit. If that limit is exceeded, this solution is discarded;
- according to expression (8), the Total Cost of a solution is the addition of operation and investment costs along the horizon. This calculation is performed considering a return rate to refer investment and operation costs to the initial year. This also means that a plan is evaluated as a whole along the planning horizon. It does not correspond to a sequence of plans, one per year, identified and evaluated in a separated way.

IV. SOLUTION ALGORITHM

The discrete nature of the expansion-planning problem justified the adoption of Simulated Annealing [13] given its natural adaptation to incorporate discrete variables and parameters and its implementation easiness. This meta-heuristic starts at an initial configuration of the system, and builds an expansion plan by sampling new installations to build or to decommission in each horizon period. Each configuration is evaluated considering investment and operation costs along the whole horizon. A new solution is then identified in the neighborhood of the current one by sampling a new installation to be built in a given period or an existing installation to decommission. After evaluating this neighbor solution, a decision is taken to accept it or not. The following paragraphs detail the application of Simulated Annealing to this 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. compute the investment costs, IC;
  - b. solve an optimization problem according to (2) to (7) to evaluate the short-term operation costs, OC, related with the current topology;
  - c. compute the Evaluation Function, TC, by (9);

$$TC^o = IC^o + OC^o \tag{9}$$

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

iii) Identify a new plan, selected in the neighborhood of the current one. To do this, sample one of the periods in the planning horizon, and then sample a new installation to build, among the ones in the list of possible additions, or to decommission, among the existing ones. The new installation will then be available in subsequent periods. 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} and IC^{new} as the addition of operation and investment costs in all periods and obtain TC^{new} ;

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

vi) If $TC^{new} \geq TC^{opt}$ then
  - a. get a random number $p \in [0,0;1,0]$;
  - b. compute the probability of accepting worse solutions $p(x^{new})$ by (10);

$$p(x^{new}) = e^{\frac{TC^{current} - TC^{new}}{K.T}} \tag{10}$$

  - c. if $p \leq p(x^{new})$ then assign x^{new} to $x^{current}$ and TC^{new} to $TC^{current}$;
  - 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 level T by a rate α smaller then 1.0;
  - b. if the new temperature level 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 BASED REMUNERATION

A. *Nodal Marginal Prices*

The marginal price of electricity in bus k at instant t can be defined as the rate of variation of the objective function of the optimization problem given that there is a change of the load at bus k at instant t. If the optimization problem is continuous and linear, marginal prices can be computed using its dual variables and they lead to a robust and efficient way of allocating costs to network users. Nodal marginal prices generally display a geographic differentiation due to transmission losses, to transmission congestion and, eventually, to the different impact of some expansion investments on the network. This leads to the problem of the time-scale in which marginal prices are computed.

B. *Computation of Short-Term Marginal Prices*

Short-term marginal prices are computed in the scope of short-term operation problems as (2) to (7). The marginal price of electricity in node k at instant t can be defined by (11). Short-term marginal prices are very volatile. They depend on the load level, on the components in operation and on generation costs, so that they can be interpreted as spot prices. If one adopts formulation (2) to (7), the marginal price at bus k for a specified load level i is given by (12).

$$\rho_k(t) = \frac{\partial OC(t)}{\partial Pl_k(t)} \tag{11}$$

$$\rho_{ik} = \gamma_i + \gamma_i \cdot \frac{\partial Loss}{\partial Pl_{ik}} - \sum \mu_{i,mn} \cdot \frac{\partial P_{i,mn}}{\partial Pl_{ik}} + \sigma_{ik} \tag{12}$$

In expression (12) and for a specified load level i, γ_i is the dual variable of the balance equation (3), Loss is an approximate function of the global losses in the network, $\mu_{i,mn}$ is the dual variable of the branch flow constraints (6) or (7) related with branch b with nodes m and n, $P_{i,mn}$ is the flow in branch m-n and σ_{ik} is the dual variable of the power not supplied constraint (5) for node k and load level i.

C. *Computation of Long Term Marginal Prices*

For a discrete problem as the one under analysis, long-term marginal prices, LTMP, can be computed with (13). In this expression, ΔTC represents the variation of the evaluation function of the Simulated Annealing algorithm if the load in bus k is changed by ΔPl_k. The variation ΔTC is due to the variations of operation costs, ΔOC, and investment costs,

ΔIC. As an example, ΔOC is computed as the difference of the operation cost of the selected expansion plan admitting that the load in bus k was increased by ΔPl_k and the operation cost of the selected expansion plan without that load variation.

$$LTMP_k = \frac{\Delta TC}{\Delta Pl_k} = \frac{\Delta OC}{\Delta Pl_k} + \frac{\Delta IC}{\Delta Pl_k} \qquad (13)$$

It should be referred that LTMP are eventually more appropriately called Long Term Incremental Prices. In fact, the discrete nature of the expansion-planning problem prevents us from defining these prices using a derivative as in (11) and, therefore, from using dual variables as in (12).

D. Marginal Based Remuneration

Once LTMP are obtained for all nodes and all periods in the planning horizon, one can obtain the Marginal Based Remuneration, MR, to assign to the transmission provider using (14). In this expression, $LTMP_{ik}$ is the long term marginal price in period i for node k, T_i is the duration of period i and Pl_{ik} and Pg_{ik} are the load and generation values in node k for period i. Finally, np is the number of periods in the planning horizon, and nnodes is the number of the nodes of the transmission network.

$$MBR = \sum_{i=1}^{np} MBR_i = \sum_{i=1}^{np} T_i \sum_{k=1}^{nnodes} LTMP_{ik} . (Pl_{ik} - Pg_{ik}) \text{ €} \qquad (14)$$

An expression similar to (14) can be used to calculate the short term marginal remuneration. In this case, one uses short-term marginal prices computed with (12). Several reports and simulations [5], [11] indicate that the short-term marginal remuneration is a small percentage of the total costs incurred by transmission companies. This is explained because short-term prices don't reflect investment costs. This is usually known as the Revenue Reconciliation Problem and is inherently addressed if we use Long-Term Marginal Prices since they reflect both operation and investment costs.

VI. CASE STUDIES

A. Portuguese 400/220/150 kV Transmission Network

In the scope of the revision of the Tariff Regulation in force since 1998, a Research Team of INESC Porto concluded a consultancy study under a contract with ERSE – the Portuguese Regulatory Board for Energy Services – to estimate the Marginal Based Remuneration of the Portuguese TSO using short term prices. The complete conclusions of this study are reported in [14] and some topics are included in [5].

In this study we considered 15 generation/load scenarios for the operation of the Portuguese 400/220/150 kV network in 1998 covering peak, full and valley hours. For each of them, we solved problem (2-7) including the iterative process to estimate branch losses and we computed nodal marginal prices using (12). Finally, expression (14) was used to compute the short term marginal remuneration. Table I presents the per hour remuneration, the duration and the remuneration in each of the scenarios. The total recovered amount corresponds to 10% of the regulated remuneration of the transmission company as approved by the Regulatory Board. For 1998, this indicates that there were no large congestion situations and the losses were reduced. This lead to very homogeneous nodal marginal prices and to reduced remunerations, except for the Peak Dry Summer, PDS, scenario that is responsible for about one third of the total amount. As a conclusion, if a marginal based tariff term was approved, there would have to be a non marginal term to recover the remaining 90% of regulated remuneration.

Table I – Per hour remuneration, duration and remuneration of each of the 15 considered scenarios.

Scenario	Per hour Remuneration (€/h)	Duration (h)	Remuneration of the Scenario (10^3 €)
PWW	2783,09	162,95	453,51
PDW	1908,33	162,95	310,96
PWSA	992,23	260,71	258,68
PDSA	1208,23	260,71	315,00
PDS	18163,69	195,54	3551,73
FWW	1426,17	436,70	622,81
FDW	1862,23	436,70	813,24
FWSA	889,68	938,57	835,03
FDSA	973,55	938,57	913,74
FDS	1567,79	1003,75	1573,67
VWW	797,10	495,36	394,85
VDW	952,09	495,36	461,63
VWSA	441,19	990,71	437,09
VDSA	587,94	990,71	582,48
VDS	518,91	990,71	514,09
		TOTAL	12038,51

B. Case Study Using a 6 bus test system [10]

Figure 2 depicts the one line diagram of a small system already used by other research teams as referred in [10]. The original system has 5 nodes, 6 branches, and generators in nodes 1 and 3. The original load is larger than the installed capacity so that a new power station will be connected to node 6.

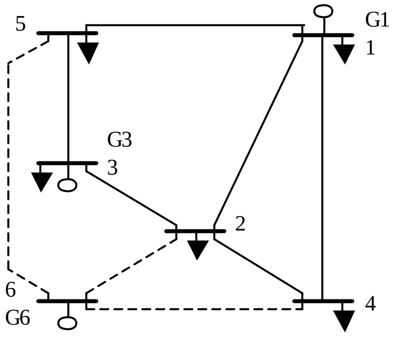

Fig. 2 – One line diagram of the 6 bus test system.

The expansion-planning problem has to address two issues – to connect node 6 to the rest of the system and to cope with a load increase of 5% along each of the 5 years in the planning horizon. Branch investment costs are given by (15) where P is the capacity in MW and L is the length in km. Although this expression, reflects a linear dependency of investment costs on the capacity and on the length of the line, other more complex expressions can be readily used. In fact, investment costs are computed for a sampled line to be built, for which a capacity and a length are known. Therefore, any other expression can be used to evaluate investment costs. Finally, we considered a return rate of 10%.

$$IC_{branch} = (0.9 + 0.3xP).L\,10^{6} \quad € \qquad (15)$$

The list of equipments to eventually build includes lines 2-6, 4-6 and 5-6 (doted lines in Figure 2). Lines 2-6 and 4-6 have a capacity of 100 MW while line 5-6 has a capacity of 78 MW. In order to simulate financial constraints, the expansion plans are constrained to include the maximum number of 6 new lines per period. Table II details the most adequate plan as identified by the described Simulated Annealing approach.

In Tables III and IV we detail the results obtained for this expansion plan. Table III presents the long term nodal marginal prices for each year evaluated using expression (13). Table IV includes the yearly marginal remuneration, YMR, obtained using expression (14) and the yearly operation, investment and total costs, YOC, YIC and YTC. All these values are referred to the initial year using a 10% return rate. Table IV also includes the Total Costs, TC, and Total Marginal Remuneration, TMR, as sums of the corresponding yearly values. Finally, the percentage of Total Costs recovered by the Total Marginal Remuneration corresponds to 86.46%.

Table II – Lines to be built and period of commissioning.

	Line 2-6	Line 4-6	Line 5-6
Period 1	2	2	2
Period 2	1	3	2
Period 3	0	0	0
Period 4	0	0	1
Period 5	0	0	1

Table III - Long Term Marginal Prices (€/kWh).

Node	Period 1	Period 2	Period 3	Period 4	Period 5
1	8.20	6.91	6.34	5.74	5.21
2	8.12	7.12	6.49	5.91	5.37
3	7.26	6.58	5.97	5.42	4.91
4	8.21	6.96	6.34	5.76	5.24
5	8.75	7.18	6.61	5.93	5.36
6	7.26	6.58	5.97	5.42	4.91

Table IV - Power Not Supplied, Costs and Remuneration.

	Period 1	Period 2	Period 3	Period 4	Period 5
PNS (MW)	0.0	0.0	0.0	0.0	0.0
YMR (10^6 €)	6237.06	3116.14	3302.03	3082.41	2956.57
YOC (10^6 €)	2443.78	1443.00	1493.15	1462.93	1438.84
YIC (10^6 €)	6008.50	5450.18	0.00	987.05	895.33
YTC (10^6 €)	8452.28	6893.18	1493.15	2449.98	2334.17
TC (10^6 €)					21622.76
TMR (10^6 €)					18694.19
TMR/TC (%)					86.46

These results deserve the some comments. In the first place it should be noticed that a large amount of investments is concentrated in period 1. This is due to the need to connect the new generator to the system and to avoid Power Not Supplied. In fact, in the initial topology, the load exceeded the installed generation capacity. Therefore, the expansion plan must include a large number of new lines in period 1 namely to eliminate Power Not Supplied. It is also important to notice that the incorporation of investment costs leads to the increase of the percentage of remuneration recovery. Just remember that this percentage varies between 10 and 20% using short term prices, and now increases to about 86%. The recovery is not complete due to the normalization of line capacities leading to topologies in which the installed transmission capacity is larger than the capacity that would be strictly necessary if a continuous model was used. This difference reflects the duality gap between the objective function of a discrete problem and the objective function of the relaxed continuous version of the same problem.

VII. CONCLUSIONS

In this paper we addressed in an integrated way the expansion-planning problem of transmission networks keeping its discrete nature. This problem is solved using a Simulated Annealing approach and it allows the incorporation of financial constraints while identifying the most suitable expansion plan considering the minimization of investment and operation costs. The model also computes nodal long-term marginal prices for each period of the horizon and the related Marginal Remuneration. Since the model includes investment costs, the Marginal Remuneration corresponds to a large percentage of the regulated one, thus addressing and partially solving the well-known Revenue Reconciliation Problem. Therefore, we think this model will be of use both in selecting transmission expansion planes and the related tariffs for use of networks.

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