PERLA: AN OPTIMIZATION MODEL FOR LONG TERM EXPANSION PLANNING OF ELECTRIC POWER TRANSMISSION NETWORKS

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ABSTRACT - This paper describes the PERLA model of Red Eléctrica de España S.A. and its application to the long term expansion planning of the Spanish transmission network. In PERLA, the network expansion is formulated as a static optimization problem minimizing the global annual cost, which aggregates the annualized investment cost, the operation cost and the reliability cost. PERLA considers a multiplicity of scenarios which are characterized by the demand, the hydraulicity and the availability of components. The network is represented by a transportation model. The resulting large linear optimization problem is efficiently solved by the Benders decomposition method. The adequacy of the model has been evaluated with detailed comparative analyses, using more accurate network models and realistic planning scenarios of the Spanish system.

Keywords - *expansion planning, transmission expansion, network planning, mathematical programming.*

1. INTRODUCTION

The objective of the ensemble of transmission network planning functions is to determine the installation plans of new facilities (lines and other network equipment) so that the resulting bulk power system may be able to meet the forecasted demand at the lowest cost, while satisfying prescribed financial and reliability criteria.

This process of transmission network planning may be typically broken down into the three following stages: Strategic Planning, Tactical Planning and Operational Planning.

Strategic Planning considers long term horizons with a very high degree of associated uncertainty. At this stage very simple models of the power system are usually employed and diverse attributes are used to evaluate the alternative plans, although formal mathematical representations of the decision making process are rarely used (see [1] and [2] for instance).

Tactical Planning of the transmission network is concerned with shorter time horizons (15 - 30 years) and its objective is to evaluate the needs for network expansion so that new equipment is installed according to its average life span. The major output of this function are the guidelines for the future structure of the transmission network. A significant degree of uncertainty still remains at this stage and the large number of possible expansion plans to be evaluated also requires the utilization of reduced power system representations. This planning stage is typically performed with the assistance of optimization models, that provide sensitivity measures for the evaluation of the resulting expansion plans and the assessment of the potential interest of alternative options. The program PERLA ("**P**lanificación **E**stática de la **R**ed de transporte a **LA**rgo plazo"), which is described in this paper, belongs to this kind of tools for tactical planning.

There are a number of aspects (e.g., those concerning transient stability limits, voltage violations, reactive power flows, short-circuit capacity, etc) which cannot be easily taken into account in long term planning models. For this reason the definitive installation decision is made at the next stage: **Operational Planning**. Here short and medium term horizons (up to 10 years) are considered, the level of uncertainty is reduced even more and fully detailed models of the power system can be used, therefore allowing the consideration of the static and dynamic aspects mentioned above.

Red Eléctrica de España S.A. (REE) is a public utility that owns and operates the Spanish electric power transmission network and is responsible for the coordinated generation dispatch of the entire system. At REE these three network planning stages are coordinated and carried out with consistent technical/economic criteria, so that they complement one another. The overall framework of the REE planning methodology may be seen in [3].

Several existing approaches are close to meet the specifications set by REE for its long term network planning model, see for instance [4] and [5]. However, it was felt that a taylor-made model would allow REE the flexibility of setting its own planning criteria, consistent with the remaining planning stages, and also of adopting the level of modeling detail that is most adequate for the specific characteristics of the Spanish system. Besides, this solution makes easier the eventual introduction of further improvements into the model.

Consequently, REE decided to develop a long term planning model in collaboration with the Instituto de Investigación Tecnológica, a universitary research group. After a review of existing methods, it was decided to make use of a modular approach in order to explore several

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modeling alternatives. The use of a decomposition technique such as Benders, see [4, 6, 7, 8, 9], was adopted to facilitate the implementation of several models and also to allow the consideration of a large number of operation scenarios without seriously impairing the efficiency of the algorithm. However, the solutions given to the treatment of the production cost and reliability models diverge from the ones in [4] and [10], since these are addressed to a power system significantly different from the Spanish one.

This paper reports the results of the first phase of development of the program PERLA. It also describes the detailed analysis which has been undertaken to check the adequacy of the present level of modeling detail in PERLA and the conclusions of this study. These conclusions, together with the solutions adopted in PERLA to cope with some specific modeling problems, may contribute to a better understanding of the long term transmission planning problem.

The next section of the paper describes the overall approach that has been used. Section 3 presents the adopted solution method. Section 4 formulates the resulting optimization problem. Operational aspects and a critical discussion of the modeling assumptions are included in section 5. In section 6, the results of the use of PERLA in a realistic Spanish transmission network planning are presented. Finally, section 7 summarizes the paper, presents the conclusions and informs about the ongoing activities to improve the tool.

2. GLOBAL APPROACH

The PERLA model obtains an optimal expansion plan of the transmission network for a prescribed horizon year, meeting the stated restrictions concerning investment and operation (in this paper, operation includes aspects belonging to production cost and reliability models). The optimal plan is the one which minimizes the total annual cost in the horizon year, resulting from the addition of investment, production and reliability costs.

The optimization problem thus stated may be formulated as a linear objective function with linear constraints. The decision variables of the problem are: on one hand, the lines to be installed and, on the other hand, the output of generation units and the power flows corresponding to the optimal dispatch for that installation. The former set of variables play a part in the investment cost and the latter in the production and reliability costs.

In addition to the described mode of use, PERLA can be employed as a production cost tool for the evaluation of expansion plans proposed by the user.

- Demand and hydraulicity characterization

In order to adequately model system operation throughout the horizon year, a number of load situations is considered. These enable the consideration of the uncertainty related to load forecasting as well as its hourly and/or seasonal load variation by means of breaking down the annual load-duration curve into different blocks of demand.

The model also takes into account the uncertainty derived from hydraulicity conditions by considering different situations with their associated probability and characterized by the hydroelectric generation output limits both for programmed and emergency situations.

At present, the model handles up to 10 load blocks and 3 hydraulicity situations.

- Electric power system representation

The electric power system is represented by a flexible model (since it allows the consideration of different levels of aggregation) where areas are linked through transmission corridors. Areas can represent the grouping of actual buses while corridors combine actual lines.

Since a transportation model (1st Kirchhoff's law) has been used to model the network, the only power flow limitation is the maximum transmission capacity of the corridors. These may be subdivided into capacity steps so as to represent each one of the integrating lines and to enable the direct assignation of situations of unavailability. The user can assign different types of lines (e.g., type of conductor, conductor disposition) to the expansion corridors.

Areas are defined by their load, hydro and thermal generation. A load level for each area is defined for every demand situation. The hydroelectric generation of each area is reduced into an equivalent unit, with no variable production cost, whose capacity is defined for every load and hydraulicity situation. Two limits of hydroelectric generation are used: the programmed value for normal conditions (energy limited) and the emergency value for post-contingency situations (power limited). Thermal generation in an area is divided into steps including one or more units. The steps can reflect the different features of thermal units (rated output, fuel type, heat rate characteristic, forced outage rate, maintenance plan) and constitute entities liable to be out of service because of a contingency. In addition, it is possible to modify their real variable production costs in order to include some extra-economic criterion in the priorities of fuel utilization.

- Investment modeling

PERLA decides the installation of new transmission lines, in order to reinforce existing corridors or to create new ones. Expansion costs include line costs as well as associated installation expenses. Costs of new substations or additional positions in existing ones at both ends of installed lines are also accounted for. The annualized value of these costs is considered (by means of a levelized carrying charge), being modified by escalation and actualization rates (so that they may be consistently compared with operation costs).

- Operation modeling

Power system operation is divided into two submodels: production cost and reliability.

The production cost model considers the "normal" state system operation. Under this condition, the aim is to economically dispatch generation units, minimizing the variable costs which comprise fuel, operation and maintenance, and unserved energy costs. PERLA considers a number of scenarios, engendered by the possible combinations of load and hydraulicity situations. For every production cost scenario, the dispatch is constrained by power balance equations in areas, generation output limits and maximum transmission capacities. The maximum transmission capacities may be reduced to simulate the approximate effect upon the corridors of a preventive security condition (by means of a previously computed "security index"). In other words, the occurrence of any contingency out of a set (e.g., N-1 contingencies) must be met without having to resort to any change in the existing optimal generation profile.

Reliability is treated in a deterministic way. The unserved energy caused by the occurrence of a set of user-specified contingencies is evaluated. Generation units are allowed to be re-dispatched following a corrective criterion, with the elimination of curtailed energy being the only objective. Every specified contingency, defined by a different availability condition, constitutes a reliability scenario which is associated to a production cost scenario. Since production costs are not considered in this part, contingencies whose economic implications are of interest are included in the production cost model. Since a large number of these contingencies would necessitate the consideration of many production cost scenarios, a simplification is made by simulating their effects through the above mentioned security index.

3. SOLUTION METHOD

The global optimization problem may be mathematically formulated as follows (with operation including production cost and reliability models, as explained before):

Minimize TC = IC(X) + OC(Y) (1)
[total cost] = [investment cost] + [operation cost]
subject to:
EXR(X) ≤ a [expansion specific constraints]
OPRX(X) + OPRY(Y) ≤ b [operation constraints]

where X represents the vector of decision variables corresponding to the network installations and Y designates the operation variables, depending on the former.

Thus the global formulation results in an optimization problem of a very large dimension, with a linear objective function subject to linear constraints. Fortunately, the two-stage (investment and operation) nature of problem (1), enables the application of the generalized Benders decomposition technique [6], therefore reducing the computer requirements of the direct resolution of the global original problem. A brief description of the method follows.

By means of a projection strategy on the X subspace, problem (1) may be formulated exclusively in terms of expansion variables, resulting in the module known as "master problem":

Minimize IC(X) + α(X) (2)
subject to: EXR(X) ≤ a

where α(X) is defined as the geometrical locus, in the X subspace, of the solutions of the following "subproblem":

Minimize OC(Y) (3)
subject to: OPRY(Y) ≤ b - OPRX(X)

The Benders method is based on the construction of a consistent approximation for the function α(X), by the so-called "Benders cuts", which are consecutively added as constraints to the master problem. These are hyperplanes obtained from the solution Y* of the subproblem (3) and inform the master problem about the influence that a marginal variation of the investment X has upon the operation costs OC(Y). They may be expressed as:

OC(Y*) + μ [X-X*] ≤ E

where OC(Y*) is the solution of (3) for the expansion X*, μ are the Lagrange multipliers associated with the solution of (3) for the expansion X* (Simplex multipliers in linear programming) and E is a scalar variable representing the estimated value of the subproblem objective function, which is a term of the master problem objective function. Therefore, the problem (2) can be written in terms of expansion variables X plus the scalar variable E:

Minimize IC(X) + E (4)
subject to: EXR(X) ≤ a
OC(Y*) + μ [X-X*] ≤ E

Let (X*,E*) be the optimal solution of problem (4). When α(X) is a convex function, as in the present problem, the Benders cuts constitute an outer piecewise linear approximation to it. Therefore, the master problem thus solved provides a lower bound to the global optimal solution [6]:

$\underline{TC}$ = IC(X*) + E*

With the expansion plan provided by the master problem, the solution of the subproblem gives an exact value of the operation cost. The pair (X*,Y*) is a feasible solution of the global problem, but not necessarily the optimum. It provides, therefore, an upper bound of the global optimum:

$\overline{TC}$ = IC(X*) + OC(Y*)

Then an iterative process is required to progressively bring near both lower and upper bounds, by means of an increasingly more accurate representation of E. The optimal solution will be reached when both bounds differ by less than a pre-established tolerance.

This methodology is advantageous in two major aspects: modularity/expansibility (i.e., some parts of the program may be easily substituted by others representing more exact models) and computational requirements (processing time is less than that of the original global problem, especially when many production cost and reliability scenarios are simultaneously considered). Experiments have been carried out with the global and decomposed versions and the results indicate that the use of Benders decomposition technique reduces computation time up to 50 times when more than 10 operation scenarios are taken into account.

Benders decomposition techniques have been successfully used in generation planning [7], reactive compensation planning [8], transmission network expansion planning [4], [9] among other applications.

4. FORMULATION OF THE DECOMPOSED MODEL

The detailed formulation of the modules resulting from the adopted decomposition approach is presented next. Each of the modules is a linear programming problem. They are solved by the MINOS optimization code [11].

- Glossary of terms

d	index of demand situation	d=1,...,D
e	index of thermal generation step	e=1,...,E_n
f	index of contingency	f=1,...,F
h	index of hydraulicity situation	h=1,...,H
i	index of iteration	i=1,...,I
I	current iteration	
k	type of line in corridor l	k=1,...,K_l
l	index of corridor	l=1,...,L
m	index of the k-type line in corridor l	m=1,...,M_{lk}
n	index of area	n=1,...,N

α coefficient including the actualized levelized carrying charge and weighing factor of the investment cost in the total cost function

β weighing coefficient of the production cost in the total cost function

γ weighing coefficient of the reliability cost in the total cost function

Ω_n set of corridors connected to area n

$\pi_{f,lk}$ sensitivity of reliability cost in scenario f to the installation of k-type lines in corridor l

$\mu_{dh,lk}$ sensitivity of production cost in scenario dh to the installation of k-type lines in corridor l

CEE_{dh} estimated production cost for scenario dh

CE_{dh} resulting production cost for scenario dh

CEN actualized cost of unserved energy

c_{ne} actualized variable production cost of the e-th thermal step in area n

$DEM_{dh,n}(DEM_{f,n})$ power demand in area n for the production cost scenario dh (reliability scenario f)

ENX maximum unserved energy in the system

$F_{dh,l}(F_{f,l})$ power flow in corridor l for the production cost scenario dh (reliability scenario f)

$FX_{dh,l}(FX_{f,l})$ power flow limit in corridor l for the production cost scenario dh (reliability scenario f)

$G_{dh,ne}(G_{f,ne})$ power output of the the e-th thermal generation step in area n for the production cost scenario dh (reliability scenario f)

$GH_{dh,n}(GH_{f,n})$ power output of hydro generation in area n for the production cost scenario dh (reliability scenario f)

$GHX_{dh,n}(GHX_{f,n})$ power output limit of hydro generation in area n for the production cost scenario dh (reliability scenario f)

$GX_{dh,ne}(GX_{f,ne})$ power output limit of the e-th thermal generation step in area n for the production cost scenario dh (reliability scenario f)

h_{lk} actualized cost of a k-type line in corridor l

ILX_l maximum investment in corridor l

IX maximum investment for the overall expansion plan

$NLKX_{lk}$ maximum number of k-type lines to be installed in corridor l

NLX_l maximum number of lines to be installed in corridor l

p_f frequency of occurrence of contingency f

p_h probability associated to the hydraulicity situation h

PNE_f estimated unserved power for reliability scenario f

PN_f resulting unserved power for reliability scenario f

$R_{dh,n}(R_{f,n})$ unserved power in area n for the production cost scenario dh (reliability scenario f)

T_d duration of the load situation d

T_f duration of the contingency f

X_{lkm} fraction of the m-th k-type line installed in corridor l

- Investment module: the master problem

The master problem minimizes the total annual cost of the system, defined as the addition of investment, production and reliability costs. These three terms, whose relative importance may be weighted at will, form the objective function (5). In (5), the investment variables are explicitly included, while each corresponding estimated production cost or unserved power is represented by a variable. All these variables are limited by the "Benders cuts", elaborated from the result of the subproblems and acting as problem constraints. Therefore the objective function to be minimized is:

$$\alpha \sum_{l=1}^{L}\sum_{k=1}^{K_l} h_{lk} \sum_{m=1}^{M_{lk}} X_{lkm} + \beta \sum_{d=1}^{D} T_d \sum_{h=1}^{H} p_h \, CEE_{dh} + \gamma \, CEN \sum_{f=1}^{F} T_f \, p_f \, PNE_f \qquad (5)$$

subject to the following linear constraints:

i) Expansion: installation variables can only vary from 0 to 1 (6), maximum number of lines in a corridor (7), maximum number of lines of a type in a corridor (8), limit of investment in a corridor (9) and total limit of investment (10).

$$0 \le X_{lkm} \le 1 \qquad l=1,...,L;\ k=1,...,K_l;\ m=1,...,M_{lk} \qquad (6)$$

$$\sum_{k=1}^{K_l}\sum_{m=1}^{M_{lk}} X_{lkm} \le NLX_l \qquad l=1,...,L \qquad (7)$$

$$\sum_{m=1}^{M_{lk}} X_{lkm} \le NLKX_{lk} \qquad l=1,...,L;\ k=1,...,K_l \qquad (8)$$

$$\sum_{k=1}^{K_l} h_{lk} \sum_{m=1}^{M_{lk}} X_{lkm} \le ILX_l \qquad l=1,...,L \qquad (9)$$

$$\sum_{l=1}^{L}\sum_{k=1}^{K_l} h_{lk} \sum_{m=1}^{M_{lk}} X_{lkm} \le IX \qquad (10)$$

ii) Reliability: maximum unserved energy of the system (11)

$$\sum_{f=1}^{F} T_f \, p_f \, PNE_f \le ENX \qquad (11)$$

iii) Benders cuts: production cost (12) and reliability (13) cuts for each iteration i=1,...,I

$$CEE_{dh} \ge CE_{dh}^{(i)} + \sum_{l=1}^{L} \sum_{k=1}^{K_l} \sum_{m=1}^{M_{lk}} \mu_{dh,\,lk}^{(i)} \left[X_{lkm} - X_{lkm}^{(i)} \right] \qquad (12)$$

$$PNE_f \ge PN_f^{(i)} + \sum_{l=1}^{L} \sum_{k=1}^{K_l} \sum_{m=1}^{M_{lk}} \pi_{dh,\,lk}^{(i)} \left[X_{lkm} - X_{lkm}^{(i)} \right] \qquad (13)$$

- Operation modules: the subproblems

When an expansion plan has been defined by the master problem for every iteration, the exact evaluation of the associated operation costs is carried out in the production cost and reliability subproblems.

For each of the D.H demand/hydraulicity scenarios there is a production cost subproblem where the following objective function is minimized:

$$CE_{dh} = \sum_{n=1}^{N} \sum_{e=1}^{E_n} c_{ne} \, G_{dh,ne} + CEN \sum_{n=1}^{N} R_{dh,n} \qquad (14)$$

For each of the F contingencies there is a reliability subproblem minimizing the following objective function:

$$PN_f = \sum_{n=1}^{N} R_{f,n} \qquad (15)$$

Both subproblems are subject to analogous constraints (a common notation is used: s describes the production cost scenario demand/hydraulicity dh as well as the reliability scenario f): maximum output for every thermal generation step in each area (16), maximum hydroelectric power in every area (17), maximum unserved energy in every area (18), transportation model equations for the electric system (19) and transmission capacity limit in every corridor (20).

$$0 \le G_{s,ne} \le GX_{s,ne} \qquad n=1,\ldots,N;\ e=1,\ldots,E_n \qquad (16)$$

$$0 \le GH_{s,n} \le GHX_{s,n} \qquad n=1,\ldots,N \qquad (17)$$

$$0 \le R_{s,n} \le DEM_{s,n} \qquad n=1,\ldots,N \qquad (18)$$

$$\sum_{l \in \Omega_n} F_{s,l} + \sum_{e=1}^{E_n} G_{s,ne} + GH_{s,n} + R_{s,n} = DEM_{s,n} \qquad n=1,\ldots N \qquad (19)$$

$$|F_{s,l}| \le FX_{s,l} \qquad l=1,\ldots,L \qquad (20)$$

Maximum output of the thermal generation steps (16) equals the rated power of the units for the peak scenarios in the production cost subproblems and in the reliability scenarios. In the remaining operation scenarios, this limit is defined by the mean availability and the maintenance schedule of generation units. The hydroelectric generation limit for the production cost subproblems is the programmed value for the respective demand/hydraulicity situation (energy consideration), while for the reliability subproblems this limit can reach the rated value of the units (power limitation).

As a result of both groups of subproblems, production costs (CE_{dh}), unserved power values (PN_f) and their sensitivities to the network expansion variables ($\mu_{dh,lk}$ and $\pi_{f,lk}$) are obtained. These values are necessary to build the Benders cuts, (12) and (13), to be sent to the master problem. In the formulation exposed here, the Benders cuts have been considered individually, for each of the operation scenarios. However, the model allows the consideration of these constraints in an aggregated way [9]. This option reduces the problem dimension, but the processing time increases since a larger number of iterations is needed.

Additionally, the statement of the problem as a two-stage decision-making process implies that the operation subproblems are all considered independently, with no predispatch conditions concerning the generation plants. Observing any coupling condition would mean adding another level into the Benders methodology. In order to determine operation costs in a more realistic way, at the end of the process the production cost model is used in dispatching mode including the generation availability resulting from the coupling of different scenarios.

5. ANALYSIS OF MODEL ADEQUACY

An extensive study of adequacy has been undertaken to determine whether the present level of detail in the representation of the long term network expansion problem suffices. Two aspects appeared to be crucial: a) the representation of the power flow by a transportation model; b) the use of continuous variables to model the naturally discrete investment decisions. Another aspect that was studied was the convenience of including the effect of losses in the production cost model.

In this analysis several models have been used and a large number of test cases have been studied, although only some representative results obtained with a reduced version of the Spanish system (46 areas and 87 corridors: see figure 1) will be reported here. The model was run with different combinations of production cost and reliability scenarios, as well as different simulated levels of insufficiency in the original network.

Figure 1. Base network (1996) and expansion plans for horizon 2005

An optimal direct current load flow (DCLF) program named JUANAC, see [12], was used to check the adequacy of the transportation model. The sensitivities of the optimal network plans provided by PERLA with respect to all the investment variables were computed with JUANAC. It has been shown [13] that the marginal savings in operation costs when transmission capacities are increased in a DC network model can be expressed as:

$$\Pi_{ij} = (\rho_i - \rho_j)\,(\Theta_j - \Theta_i) \qquad (21)$$

where ρ_i and Θ_i are respectively the spot price and angle of node i.

An important feature of this expression is that it applies to any investment variable, regardless of whether the line has been installed or not. Therefore, every investment decision that is made by PERLA can be verified by comparing the sensitivity from (21) with the marginal investment cost. The comparison may indicate that more investment is needed, that PERLA has overinvested or that the solution from PERLA is indeed nearly optimal.

The left side of table 1 summarizes the results from one of the test cases, with an initial network that was heavily underdeveloped. The first two columns show the solution that is provided by PERLA. The third column indicates whether PERLA has overinvested (OVER), underinvested (UNDER) or has optimally invested (OPT) for each of the expandable corridors, always according to the sensitivities obtained with the DCLF model. Since sensitivities only contain local information, in the fourth and fifth columns it has been indicated whether the total investment plus operation cost increases (INCR), decreases (DECR) or remains unaltered when discrete changes are made to PERLA investment solutions. In the fourth column every expansion variable has been increased up to one, while in the fifth column they have been individually decreased down to zero.

Inspection of the left part of table 1 and similar results from other example cases lead one to conclude that most of the investment decisions made by PERLA are correct, although PERLA often incurs in the oversight of profitable investments because of its simplified representation of the network.

CORRIDOR	PERLA EXPANSIO N	DC model SENSITIVITIES	DC model investment up to 1	DC model investment decrease to 0	EXPANSIO N discrete variab transp model	DC model SENSITIVITIES
33 - 37	0,1060	OPT	INCR	INCR	1	OVER
34 - 35	0,6266	OPT	INCR	INCR	1	OVER
31 - 34	1,0000	OPT	INCR	INCR	1	UNDER

15 - 17	0,3881	UNDER	DECR	INCR	1	UNDER
28 - 29	0,8907	UNDER	DECR	INCR	1	OPT
9 - 41	0,3738	UNDER	DECR	INCR	1	UNDER
25 - 33	0,1805	UNDER	DECR	INCR	1	OVER
35 - 37	0,6018	UNDER	DECR	INCR	0	UNDER
36 - 38	0,4330	UNDER	DECR	INCR	0	UNDER
14 - 16	0,2432	UNDER	DECR	INCR	0	UNDER
21 - 22	0,2863	OVER	INCR	DECR	0	OPT
9 - 24	0,0000	UNDER	DECR	------	0	UNDER
23 - 44	0,0000	UNDER	DECR	------	1	UNDER
23 - 45	0,0000	UNDER	DECR	------	0	UNDER
24 - 25	0,0000	UNDER	DECR	------	0	UNDER
25 - 26	0,0000	UNDER	DECR	------	0	OPT
26 - 27	0,0000	UNDER	DECR	------	0	OPT
29 - 30	0,0000	UNDER	DECR	------	0	OPT
9 - 10	0,0000	UNDER	DECR	------	0	UNDER
10 - 25	0,0000	UNDER	DECR	------	1	UNDER
21 - 23	0,0000	UNDER	DECR	------	0	UNDER
3 - 39	0,0000	OPT	INCR	------	0	OPT
22 - 28	0,0000	OPT	INCR	------	0	OPT

Table 1. Comparative results of network expansion planning.

The second major modeling aspect that was analyzed was the use of continuous decision variables in the master problem. Now the results from PERLA were compared to the discrete solutions provided by a mixed integer program (ZOOM from XMP Inc. [14] was used here) which was applied to the non-decomposed formulation of the same optimization problem as in PERLA. This discrete plan is shown on the right side of table 1, together with the results of the sensitivity analysis of this plan using JUANAC again.

Inspection of these and other similar results indicated that discrete plans have a larger overall level of investment than continuous ones (9 versus 5.13 lines in this example). Besides, it was learned that there is no obvious procedure to turn an optimal solution in continuous variables into its "corresponding" integer optimal solution.

Figure 2 shows a representation of the general complementarity and overlapping of the four models resulting from the duality of the two aspects studied here.

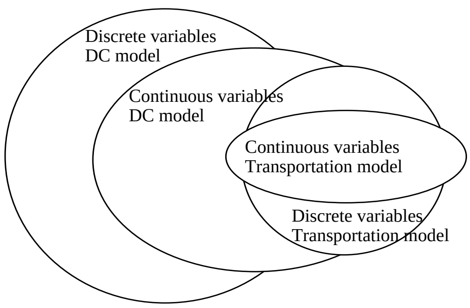

Figure 2. Comparative situation of the solution plans

The convenience of incorporating losses into the network model was also investigated using JUANAC. The point here was to check whether investment in new lines could be partly justified in a significant way by the savings (both in operation costs and in unnecessary investments) associated to loss reduction. Although the results of this study were not conclusive (probably because the investments suggested by PERLA were obviously not addressed towards loss reduction) it was decided to include ohmic losses into the network model to be used in the next phase of development of PERLA.

Table 2 presents data of the resulting CPU time after running PERLA under different conditions of electric system size (S1 corresponds to 46 areas and 87 corridors, S2 to 99 areas and 152 corridors), number of expansion options, number of operation scenarios and the need for network development in the base year. All data correspond to a DEC computer model VAX 8800.

Problem characteristics				Iter	CPU time (s)		
Elect syst	Need of developtm	Expan corridor	Operat scenar		per iteration Master	Subproblem	total
S1	Low	41	4	7	10.29	19.27	229
S1	Low	3	4	6	0.81	16.49	122
S1	High	41	4	30	29.85	19.28	1496
S2	Low	5	4	4	0.72	7.59	60
S2	Low	5	35	4	0.97	200.81	1012
S2	High	29	35	24	3.64	206.17	5234

Table 2. Computation time

6. HORIZON 2005: A LONG TERM EXPANSION PLAN FOR THE SPANISH TRANSMISSION NETWORK

This section describes the first application of PERLA to an actual network expansion problem within the integrated planning methodology of REE. The year 2005 was chosen as the static horizon, being 1996 the base year. Since at present no definitive generation expansion plan has been drawn up for this horizon it has been necessary to introduce assumptions about the location of new plants. Therefore, the results which are reported here do not represent definitive plans but a first approximation to them. Because of this uncertainty, several alternative generation expansion hypotheses have been considered, as well as scenarios with different fuel costs and other economic indexes.

At present, the Spanish power system must meet a maximum peak load of 22000 MW and an annual energy demand of 130000 GWh. The installed generation capacity is 42635 MW (16148 MW are hydro, 10683 MW coal, 7967 MW oil/gas and 7837 MW nuclear). The transmission network includes 12714 km of 400 kV and 14921 km of 220 kV.

The power system for the adopted base year (1996) has been obtained from the addition of the expansion plans currently approved to the present power system. For the reported study the complete 400 kV and 220 kV base year transmission network has been reduced to a more manageable size (46 areas and 87 corridors). At present, PERLA is also being used with the entire 400 kV network (99 areas ann 152 corridors).

In the production cost model just two hydraulicity situations have been considered. Although PERLA can handle up to 10 demand situations, in this study only two have been included. The first one, with a short duration (25 h) tried to represent the network capacity limitations to satisfy the peak demand; the second one, with the same level of load and the remaining equivalent duration (so that the annual energy demand is considered), was addressed to model the average operating conditions.

Reliability aspects have been taken into account under a double viewpoint. The N-1 criterion has been represented in a "preventive" way in the production cost subproblem, so that the system must be able to withstand any single contingency without incurring in overloads and without making any changes to the current generation dispatch. A previous and detailed study of contingencies allowed the definition of a coefficient of reduction of the capacity of the lines, so that any reasonable dispatch that met these fictitious capacity limits would also satisfy the N-1 preventive criterion. A small number of preselected N-2 and higher contingencies have been accounted for with a "corrective" criterion (i.e., by allowing the system to modify the dispatch of the thermal units and also of the hydro units up to their emergency values). A separate reliability subproblem has been used to represent each contingency.

Figure 1 shows the location of the new installations suggested by PERLA, where it can be appreciated the low amount of investment that is required for the prescribed load and generation hypothesis.

The adequacy of the optimal solutions provided by PERLA for the horizon 2005, under two different hypotheses of generation, has been checked again with a DCLF tool that is used for operational planning. The performance of the optimal network for the reference case and for each one of the N-1 contingencies was tested with the DCLF program and a quasi-optimal solution was manually developed by a trial-and-error procedure. The exercise was repeated under different economic scenarios and the results are summarized in table 3, where the new lines have been classified into 2 categories: those which are necessary in all the scenarios and the ones which are only needed under unlikely conditions.

An ample coincidence of both approaches can be observed, concerning the installation of major expansion options. It has been checked that the reason for the existing discrepancies is twofold. In the first place some sections of the network had not been properly modeled (due to the aggregation of nodes into the same area and the consequent ignorance of some lines as well as a deficient modeling of the 220 kV level), therefore resulting in nonexistent network needs. In the second place, the aggregated treatment of all the N-1 contingencies in PERLA by means of a single security coefficient was shown to provide only a good approximation to the individual analysis of each contingency. Again, it was concluded that the results from PERLA could be trusted and that, because of PERLA's tendency to underinvest, they could be used as the core of the long term expansion plan.

	PERLA	CONVENTIONAL METHOD
HYPOTHESIS. 1		
Always	31-35 (x2)	31-35 (x2) 32-33
Sometimes	20-21	31-34 25-27
HYPOTHESIS. 2		
Always	31-35 (x2) 28-29	31-35 (x2)
Sometimes	15-42 18-46 20-21 26-46	31-34 25-27 20-21

Table 3. Alternative expansion plans for the 2005 horizon.

7. CONCLUSIONS AND DIRECTIONS FOR FURTHER WORK

The paper has presented the current status of the development of the model PERLA and its integration within the overall planning approach of Red Eléctrica de España. A significant effort has been devoted to the task of checking the adequacy of the plans that are obtained with the present version of the model so that sound decisions can be made concerning further extensions.

After the application of PERLA to a number of example cases, including some of the studies currently performed at REE for the 2005 horizon, it has been found that the results are sound and useful and they enable the planning team a more selective use of conventional tools. However, PERLA is biased towards underinvestment because of its simple representation of the network, and it has been learned that rounding-off its continuous investment variables is by no means an easy task. Therefore, a new phase of development of PERLA is presently under way, with discrete decision variables in the master problem, a hybrid (DC-transportation) network model with losses in the operation subproblems and a more precise characterization of the N-1 contingencies, while preserving the overall structure and modeling philosophy of the present program.

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