Probabilistic Mid-Term Transmission Planning in a Liberalized Market

P. Sánchez-Martín, A. Ramos and J.F. Alonso

***Abstract*--This paper shows a new transmission planning methodology for a liberalized electricity market. This methodology analyzes power exchange scenarios using a transmission adequacy linear programming model. Dual variables of this adequacy model are used to compute transmission investment sensitivities. This methodology evaluates jointly non-supply demand, n-1 network preventive adequacy level and power exchange deviations. After sampling generator & consumer bidding and generator & network failures, sensitivity means, their confidence intervals & validity ranges are analyzed. Finally, an extended Garver's six-bus and a Spanish system cases are analyzed.**

***Index Terms*-- Transmission expansion planning, investment sensitivities, n-1 security preventive criteria, liberalized market.**

I. Introduction

DURING the last decade, the increasing liberalization of electricity markets has somehow redefined transmission planning objectives. Some of these objectives come from a centralized regulation framework, i.e. to supply system demand at a low cost and high security conditions [1]. In liberalized generation markets, those previous objectives should be compatible with improving the efficiency of power exchanges among market participants [2]. Several European electric systems, such as the Spanish and England & Wales ones, combine a liberalized generation market with a regulated transmission system.

Some approaches have been designed to deal with simultaneous competition on generation and transmission activities [3] & [4]. As an alternative, this work describes a method to determine marginal transmission investments for improving power exchange efficiency in a liberalized generation market. This methodology simulates power exchange scenarios which are cleared by the Market Operator (MO) using the MO model and then, they are analyzed considering transmission adequacy criteria used by the System Operator (SO).

Based on the classification given by [5], this new transmission planning methodology can be classified as probabilistic and static because sampled system scenarios are analyzed for a specific time horizon. These sampled scenarios provide a more realistic perception of the transmission investment problem in the context of a liberalized market. The inverse transform method has been used to sample bids and system failures.

Transmission is modeled using a DC approximation including network losses [6] and system reliability is based on n-1 preventive adequacy criterion [7] & [8], by means of a linear programming model, the SO model. Linear programming provides dual variables to compute investment sensitivities as well as their ranges of validity.

Analyzing hundreds of simulated scenarios with integer and non-linear planning models, [9], [10] & [11], would require a huge computational cost, while metaheuristic and heuristic solving techniques would provide close to optimal solutions at lower computational costs, [12], [13] and [14]. However, these latter procedures do not provide the necessary sensitivities to analyze transmission reinforcements.

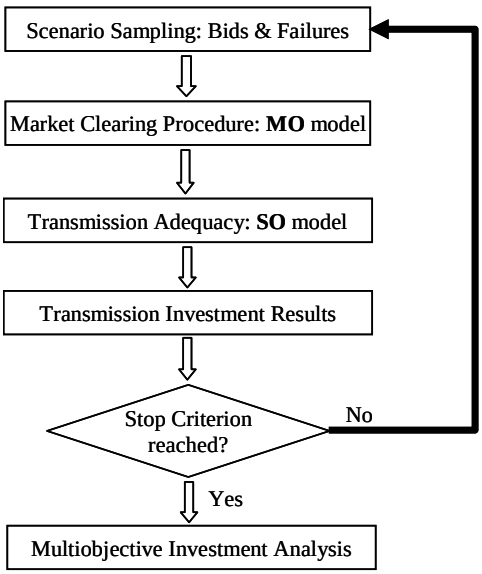

Fig. 1. Methodological Scheme

This paper describes the model approach and the

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transmission planning methodology depicted at

Fig. 1. This paper is divided into seven sections. After this first introductory section, the second section describes the scenario sampling mechanism, the third section shows the modeling of market clearing procedure (MO). Transmission adequacy model is described mathematically in the fourth section. Expressions of transmission investment sensitivities are explained in the fifth section. In the sixth section, the procedure to analyze investments is described. At seven and eight sections, Garver's extended six-bus and the Spanish case analyses are shown.

II. Scenario Sampling

Each scenario represents a possible energy profile resulting from generator and demand bids, as well as a system availability status derived from generator and circuit failures,

Fig. 1. Generation and demand bid sampling is detailed for each unit considering historical bidding data, estimated future evolution of technological costs, specific generator lifecycle, future prices of fossil fuels and probabilistic distributions of wind and hydro productions.

The inverse transform method [15] has been used to sample hundreds of bidding scenarios. Generation & network failures have been sampled using Bernoulli distributions based on their previous failure rates. Hydro & wind energy blocks are sampled using triangular distributions whose parameters are computed based on historical data analysis. Generation & demand block prices are sampled using a time series structure containing tendency, cyclic and random components. These components should be computed taking into account regional and international future economic & environmental analysis, fuel price forecasting and generation and demand characteristics.

III. Market clearing procedure: The MO model

On a daily basis, generators and consumers submit hourly bids to the MO which clears them and then determines the hourly system marginal price to maximize energy exchange among participants. Then, selling and buying bids are exchanged at this marginal price. This section explains how this MO procedure has been implemented for each scenario.

Each generator u for each hour h divides its bid into b blocks whose energy amount is symbolized by $q_{u,h,b}$ and whose prices are noted by $p_{u,h,b}$. Analogously, consumer at node n submits $q_{n,h,b}$ energy blocks whose prices are noted by $p_{n,h,b}$.

For each scenario MO procedure ranks generation bids from low to high prices and demand bids in the opposite direction. After this ranking, a simple repetitive procedure clears the highest demand bid with the lowest generation bid. Both bids are eliminated from the list and this procedure continues until no more bids can be cleared. Energy marginal price of hour h, λ_h, is the highest price at which a demand bid has been cleared. Generators' and consumers' cleared energy blocks are noted by $q^0_{u,h,b}$ and $q^0_{n,h,b}$.

This procedure is based on a single node system model where transmission losses estimation is considered as an additional demand. Other clearing details such as minimum daily income, non-separable bidding blocks and ramp rates conditions may be added to the procedure.

IV. Transmission adequacy model: the SO model

After completing the MO procedure, some cleared bids are modified by the SO to comply with network constraints and

system adequacy conditions, such as circuit limits, transmission losses and n-1 preventive adequacy criterion.

The SO model is formulated as a linear programming model. Its objective function minimizes system unserved demand, non-fulfillment of network n-1 preventive criterion and power exchange deviations (1).

$$\min \sum_{h,n} q_n \cdot U_{n,h} + \sum_{h,u}\sum_{b} p_{u,h,b} \cdot \Delta G_{u,h,b} - \sum_{h,u}\sum_{b} \lambda_h \cdot \nabla G_{u,h,b} + \sum_{h,l}\sum_{l'} w_l \cdot \left(\Delta O_{l,l',h} + \nabla O_{l,l',h}\right) \quad (1)$$

Each component of this objective function has a different weight. Nodal unserved energy $U_{n,h}$ is weighted by the q_n penalization parameter. Power exchange deviations are weighted depending on their directions. Upwards deviations, $\Delta G_{u,h,b}$, i.e. increment in generator production, are paid by the MO based on the specific generator bid, $p_{u,h,b}$. Downwards deviations, $\nabla G_{u,h,b}$, i.e. reduction of generator production, are not paid by the MO taking into account the system hourly marginal price, λ_h. Overloads of circuit l after failure of circuit l', $\Delta O_{l,l',h}$ and $\nabla O_{l,l',h}$, are penalized by the parameter w_l.

$$\begin{aligned} &\sum_{u\to n}\sum_{b} q^0_{u,h,b} + \sum_{u\to n}\sum_{b} \Delta G_{u,\,h,\,b} - \sum_{u\to n}\sum_{b} \nabla G_{u,h,\,b} \\ &+ \sum_{l\to n} (F_{l,h} - \frac{1}{2} R_{l,h}) - \sum_{l\leftarrow n} (F_{l,h} + \frac{1}{2} R_{l,h}) \\ &= \sum_{b} q^0_{n,h,b} - U_{n,h}\,;\ \forall n,h \qquad :\ \pi_{n,h} \end{aligned} \quad (2)$$

Nodal energy balance equation, i.e. first Kirchoff law, is included into the SO model with the equation (2). All generation units at node n, noted by $u \to n$, sum their cleared bids $q^0_{u,h,b}$ to theirs upwards deviations and subtract downwards deviations. Then, this generation power at node n is added to the net transmission power inflows at node n.

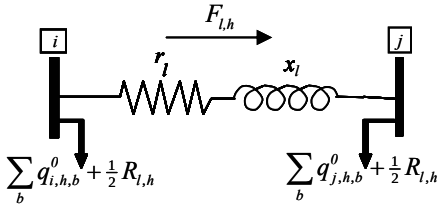

Fig. 2. Extended Π model of circuit l

Lossless power flow of circuit l is noted by $F_{l,h}$. Ohmic losses of circuit l at hour h, due to its resistance r_l, are noted by $R_{l,h}$. All circuits whose flows go to node n, noted by $l \rightarrow n$, add their net energy to the nodal balance and flows that come from node n, noted by $l \leftarrow n$, subtract their net energy at equation (2). Ohmic losses at each circuit are modeled as demands at its extreme nodes, Fig. 2. Those demands are subtracted from the lossless power flow (2). This nodal balance supplies the hourly demand unless unsupplied energy is set, $U_{n,h}$.

$$F_{l,h} = \frac{\left(\theta_{i,h} - \theta_{j,h}\right)}{x_l} \;\; ; \;\; \forall l \tag{3}$$

Power flow of each circuit is computed using a DC modeling (3), dividing voltage angle difference, ($\theta_{i,h}$-$\theta_{j,h}$), by its circuit reactance, x_l. Circuit losses are approximated using a piecewise linear formulation. This piecewise formulation divides circuit angle difference into $2T$ angular increments (4), $\delta_{l,h,t}$, Fig. 3. These increments are multiplied by circuit slopes, $m_{l,t}$ (5). This linear formulation approximates a more accurate non-linear expression (6), where g_l is the conductance of circuit l. This approximation has been used in [6] & [8]. As losses approximation function is convex & objective function tries to minimize losses indirectly, angular increments are filled from the origin to one side direction depending on the angular difference sign.

$$\theta_{i,h} - \theta_{j,h} = \sum_{t=1}^{T} \delta_{l,h,t} - \sum_{t=T+1}^{2T} \delta_{l,h,t} \tag{4}$$

$$R_{l,h} = \sum_{t=1}^{2T} m_{l,\,t} \cdot \delta_{l,h,t} \tag{5}$$

$$R_{l,h} = 2 \cdot g_l \cdot \left(1 - \cos\left(\theta_{i,h} - \theta_{j,h}\right)\right) \tag{6}$$

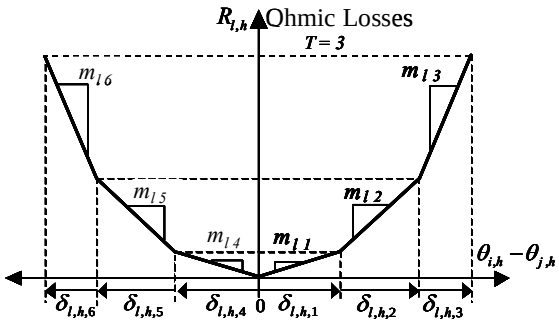

Fig. 3. Losses piecewise linear approximation

To implement transmission n-1 preventive criterion, every circuit failure is analyzed to determine postfailure overloads in other circuits. Circuit failures that are excluded from this preventive analysis are those that would isolate part of the system.

Flow of circuit l after circuit l' failure is computed using network sensitivities $\alpha_{l,l'}$ [7]. These sensitivities determine the flow increment in circuit l when there is a decrement of flow in circuit l' (7). This expression contains elements of the inverse of admittance matrix, Z, and reactances of circuits, x_l & $x_{l'}$. Nodes of failed circuit l' are symbolized by m and n, and nodes of circuit l by i and j. These sensitivities must be updated at every scenario taking into account network topology changes.

$$\alpha_{l,l'} = \frac{\Delta F_l}{\nabla F_{l'}} = \frac{x_l}{x_{l'}} \cdot \frac{z_{m,i} - z_{m,j} - z_{n,i} + z_{n,j}}{x_{l'} - z_{m,m} + 2 \cdot z_{m,n} - z_{n,n}} \tag{7}$$

Postfailure flow of circuit l after the failure of circuit l' is divided into three components: $FP_{l,l',h}$, non-overloaded power flow of circuit l, $\Delta O_{l,l',h}$ and $\nabla O_{l,l',h}$, overloaded flow ranges of circuit l in both directions (8).

$$F_{l,h} + \alpha_{l,l'} \cdot F_{l',h} = FP_{l,l',h} + \Delta O_{l,l',h} - \nabla O_{l,l',h} \tag{8}$$

Bounds of SO variables take into account MO clearing results, $q^0_{u,h,b}$ and $q^0_{n,h,b}$. Positive generation deviations are limited by the difference between the original bid and the cleared bid, $q_{u,h,b}$ (9). Negative generation deviations are limited by the cleared bid, $q^0_{u,h,b}$ (10). Unserved demand is limited by the blocks of the cleared demand bid (11).

Non-overloaded prefailure and postfailure flows are limited to the circuit capacity, F_l^{max}, (12) & (13). Dual variables on those former bounds, $\pi_{Fl,h}$ & $\pi_{FPl,h}$, are used to compute transmission reinforcement sensitivities. Overloaded ranges of postfailure flows are not limited in both directions (14). Voltage angles are limited to π radians (15). Bounds on ranges of voltage angular difference to model circuit ohmic losses (16) are computed by the resolution of a least squares problem [8].

$$0 \le \Delta G_{u,h,b} \le q_{u,h,b} - q^0_{u,h,b} \tag{9}$$

$$0 \le \nabla G_{u,h,b} \le q^0_{u,h,b} \tag{10}$$

$$0 \le U_{n,h} \le \sum_b q^0_{n,h,b} \tag{11}$$

$$-F_l^{\max} \le F_{l,h} \le F_l^{\max} \;\; : \pi_{F_{l,h}} \tag{12}$$

$$-F_l^{\max} \le FP_{l,l',h} \le F_l^{\max} : \pi_{FP_{l,h}} \tag{13}$$

$$0 \le \Delta O_{l,l',h}, \nabla O_{l,l',h} \le \infty \tag{14}$$

$$0 \le \theta_{i,h} \le \pi \tag{15}$$

$$0 \le \delta_{l,h,t} \le \delta_{l,t}^{\max} \tag{16}$$

V. Transmission Investment Sensitivities

Transmission investments are classified as reinforcements (uprating existing circuits) and expansions (new circuits or transformers). In general, sensitivities provide information about improvements in the objective function versus capital investments in transmission assets. These sensitivities are computed using dual variables of some SO model constraints.

Sensitivities of circuit reinforcements make the assumption that the increment of the capacity of circuit l, ΔF_l^{max}, is proportional to the capital investment, ΔI_l [16]. That ratio is noted by $k_{f,l}$ and depends on the type of reinforcement technology (17). Besides, reinforcements assume that electric parameters of reinforced circuits do not change.

$$\frac{\Delta F_l^{\max}}{\Delta I_l} = k_{f,l} \tag{17}$$

To compute circuit reinforcement sensitivities, ρ_l, dual variables of expressions (12) and (13), π_{Fl} and π_{FPl}, are used (18).

$$\rho_l = \frac{\Delta obj.function}{\Delta I_l} = \frac{\Delta o.f.}{\Delta F_l^{max}} \cdot \frac{\Delta F_l^{max}}{\Delta I_l} = \left(\pi_{F_{l,h}} + \pi_{FP_{l,h}}\right) \cdot k_{f,l} \tag{18}$$

Circuit expansion sensitivities assume a direct proportion, $k_{y,l}$, between new circuit admittance, y_l, and capital investment, I_l (19), and also another proportion, $k_{g,l}$, between new circuit conductance, g_l, and capital investment, I_l (20).

$$k_{y,l} = \frac{y_l}{I_l} \tag{19}$$

$$k_{g,l} = \frac{g_l}{I_l} \tag{20}$$

Dual variables of constraint (2), $\pi_{n,h}$, are used to evaluate expansion sensitivities, γ_l. To improve their accuracy, transmission losses have been evaluated using the cosenoidal expression (6). Expansion sensitivity expression uses pre-expansion voltage angle on extreme nodes of the new circuit l, θ_i^0 y θ_j^0, (21). This expression has been obtained taking into account the dual variable definition at the SO model.

$$\gamma_l = \frac{\Delta obj.function}{\Delta I_l} = \frac{\Delta o.f.}{\Delta y_l} \cdot \frac{\Delta y_l}{\Delta I_l} + \frac{\Delta o.f.}{\Delta g_l} \cdot \frac{\Delta g_l}{\Delta I_l} = \left(\pi_i - \pi_j\right) \cdot k_{y,l} \cdot \left(\theta_i^0 - \theta_j^0\right) + \left(\pi_i + \pi_j\right) \cdot k_{g,l} \cdot \left(1 - \cos\left(\theta_i^0 - \theta_j^0\right)\right) \tag{21}$$

Expansions that connect isolated nodes to the system have a different sensitivity expression, (22).

$$\gamma_l = \frac{\Delta objective\ function}{\Delta I_l} = \left(\pi_i - \pi_j\right) \cdot k_{f,l} + \left(\pi_i + \pi_j\right) \cdot k_{g,l} \cdot \left(1 - \cos\left(k_{f,l} \Big/ k_{y,l}\right)\right) \tag{22}$$

VI. Transmission Investment Analysis

Transmission investment analysis provides a set of network expansions and reinforcements to add to the system. This set is obtained after completing several stages. At each stage, a set of sampled system scenarios is evaluated and so, several statistical and deterministic results for each individual expansion and reinforcement are obtained,

Fig. 1. Then, one transmission investment is chosen based on a multiattribute criterion that weights those outputs jointly. Next stage repeats the procedure adding the chosen transmission investment to the system which also includes previous transmission investments, Fig. 4.

One type of statistical outputs are means and confidence intervals of investment sensitivities. Other type of statistical outputs are means of validity ranges of investment sensitivities. Those validity ranges are computed as the minimum range of dual variables of constraints (18), (21) and (22).

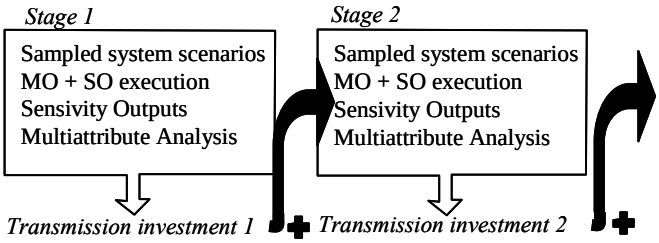

Fig. 4. Transmission Investment Analysis

Deterministic outputs of this analysis are, for instance, capital investments, technological adequacies and environmental impacts. These outputs are specifically weighted by the user.

VII. Garver´s Study Case

Original Garver´s six-bus system [17], solid part of Fig. 5, has been extended with bidding data for generators and consumers. Generators´ hourly energy bids are shown at Table I. Uncertainty on generation prices has been modeled using a normal distribution whose mean value is at Table I and a standard deviation of 5 $/MWh. Negative sampled prices are truncated to zero price. Consumers´ hourly energy bids are shown at Table II. These consumption values are modeled as constants. Generation failures are modeled using a failure rate of 10% for each generator. Transmission failures are modeled using a failure rate of 1% for each circuit.

Table III illustrates possible transmission expansions taken from [4]. No reinforcements have been included in this analysis.

TABLE I
GENERATORS´ ENERGY BIDS

Node	1st Block		2nd Block		3rd Block	
	[MW]	[$/MWh]	[MW]	[$/MWh]	[MW]	[$/MWh]
1	50	9	50	10	50	11
3	120	18	120	20	120	22
6	200	27	200	30	200	33

TABLE II
CONSUMERS´ ENERGY BIDS

Node	1st Block		2nd Block		3rd Block	
	[MW]	[$/MWh]	[MW]	[$/MWh]	[MW]	[$/MWh]
1	56	150	16	35	8	30
2	168	150	48	35	24	30
3	28	150	8	35	4	30
4	112	150	32	35	16	30
5	168	150	48	35	24	30

TABLE III
POSSIBLE TRANSMISSION EXPANSIONS

Circuit	Resistance [per unit]	Reactance [per unit]	Capacity [MW]	Investment [M$]
1-2	0.10	0.40	100	40
1-3	0.09	0.38	100	38
1-4	0.15	0.60	80	60
1-5	0.05	0.20	100	20
1-6	0.17	0.68	70	68
2-3	0.05	0.20	100	20
2-4	0.10	0.40	100	40
2-5	0.08	0.31	100	31
2-6	0.08	0.30	100	30
3-4	0.15	0.59	82	59
3-5	0.05	0.20	100	20
3-6	0.12	0.48	100	48
4-5	0.16	0.63	75	63
4-6	0.08	0.30	100	30
5-6	0.15	0.61	78	61

Each stage samples 1000 scenarios of the Garver´s system and then one transmission expansion is chosen based on a multiattribute criterion. Eight decision stages are detailed at Table IV. Three best candidates per stage, based on sensitivity means, are shown in the second column. The bold one is the chosen expansion. Then, means and confidence intervals of sensitivities are depicted in the third and fourth column. Fifth column shows means of validity ranges of sensitivities. Last column shows the multiattribute value for each expansion at each stage. This multiattribute value is computed weighting 45% for sensitivity mean ratios, 45% for validity range ratios and 10% for sensitivity confidence interval ratios. Those ratios are computed dividing each type of outputs by the respective mean of the best three candidates.

TABLE IV
ITERATIVE INVESTMENT RANKING

Stage	Candidates	Sensitivity mean [M$/M$]	Confidence interval [%]	Validity range [MW]	Multi-attribute value
No circuit is added (initial stage)					
1	**2-3**	**-0.761**	**2.0**	**221**	**0.973**
	3-5	-0.746	2.3	218	0.942
	2-6	-0.484	2.0	221	0.785
Circuit 2-3 is added					
2	**2-6**	**-0.491**	**2.9**	**240**	**1.007**
	3-5	-0.487	2.2	210	0.937
	4-6	-0.684	56.0	176	0.756
Circuits 2-3 and 2-6(a) are added					
3	**4-6**	**-1.142**	**56.5**	**181**	**1.164**
	3-5	-0.538	32.3	208	0.905
	2-4	-0.533	89.8	140	0.632
Circuits 2-3, 2-6(a) and 4-6(a) are added					
4	**3-5**	**-0.677**	**2.5**	**203**	**1.237**
	2-5	-0.293	4.0	203	0.780
	4-6	-0.290	3.3	155	0.683
Circuits 2-3, 2-6(a), 4-6(a) and 3-5 are added					
5	**4-6**	**-0.387**	**3**	**176**	**1.036**
	2-6	-0.345	3.2	167	0.945
	3-6	-0.195	3.2	164	0.719
Circuits 2-3, 2-6(a), 4-6(a), 3-5 and 4-6(b) are added					
6	**2-6**	**-0.097**	**12**	**164**	**1.075**
	4-6	-0.062	12.9	169	0.856
	3-6	-0.051	13.7	165	0.769
Circuits 2-3, 2-6(a), 4-6(a), 3-5, 4-6(b) and 2-6(b) are added					
7	**2-6**	**-0.061**	**15.8**	**161**	**1.070**
	5-6	-0.035	12.9	163	0.873
	3-5	-0.061	16.0	70	0.757
Circuits 2-3, 2-6(a), 4-6(a), 3-5, 4-6(b), 2-6(b) and 2-6(c) are added					
8	**3-5**	**-0.073**	**13.2**	**88**	**1.265**
	1-5	-0.043	16.5	40	0.653
	2-5	-0.032	18.1	76	0.781
No more circuits are added					

Original and expanded Garver´s system are illustrated at Fig. 5. Original Garver's circuits are drawn with solid lines and expansions, such as 2-3, 2-6(a)(b)(c), 4-6(a)(b) and 3-5, are drawn with dotted lines.

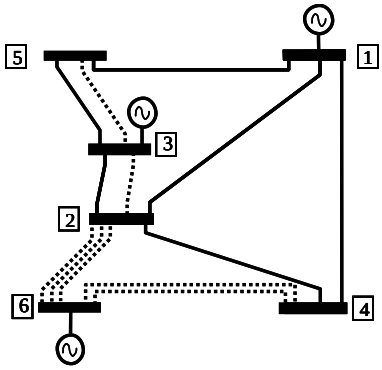

Fig. 5. Original and expanded Garver´s system

As Fig. 6 shows, unsupplied demand is reduced asymptotically to zero as more circuits are added to the system. Cumulative investment cost increases almost linearly with the number of circuits due to all those circuits have similar individual costs.

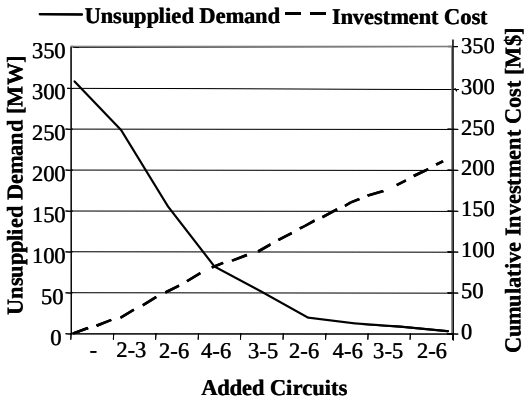

Fig. 6. Garver´s unsupplied demand and Investment Cost

As Fig. 7 shows, the operation cost decreases to a M$ 2 as transmission investment increases. The system operation cost includes penalizations due to unserved demand, preventive network overloads and exchange deviations.

First transmission expansions diminish drastically unserved system demand and then, energy flows through the network flows increase. The higher network flows are, the more postfailure overloads and transmission losses exist. Nevertheless, after three first expansions output improvements are smaller.

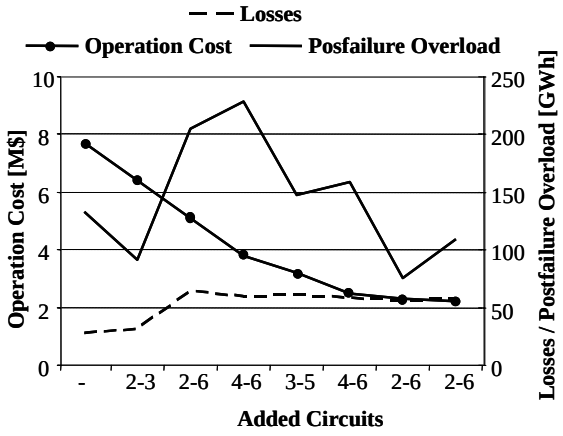

Fig. 7. Operation results evolution vs. added circuits

VIII. Spanish Study Case

The Spanish case has been analyzed by this planning methodology. This case contains 623 nodes and 1021 circuits, 165 thermal groups and 76 hydro units. Twelve possible transmission expansions, detailed by their extreme node numbers, have been evaluated. Each decision stage samples 100 scenarios for the system to obtain the three best choices. Table V contains statistical results and multicriteria values per stage. The multicriteria value has been obtained as in Section VII. The best transmission expansion for each stage is progressively added to the system.

TABLE V.
SPANISH ITERATIVE INVESTMENT RANKING

Stage	Candidates	Sensitivity mean [M$/M$]	Confidence interval [%]	Validity range [MW]	Multi-attribute value
No circuit is added (initial stage)					
1	**431-461**	**-5.622**	**8.6**	**296**	**1.505**
	390-403	-3.365	7.9	119	0.767
	570-583	-1.254	63.4	131	0.727
Circuit 431-461 is added					
2	**586-588**	**-3.275**	**57.5**	**138**	**1.162**
	390-403	-3.352	7.9	107	0.941
	570-583	-1.849	56.8	128	0.897
Circuits 431-461 and 586-588 are added					
3	**390-403**	**-3.633**	**6.9**	**157**	**1.468**
	570-583	-0.289	39.1	138	0.894
	424-520	-2.841	7.9	6	0.638
Circuits 431-461, 586-588 and 390-403 are added					
	570-583	**-0.587**	**51.4**	**129**	**1.434**
4	424-520	-2.930	7.8	5	0.821
	500-567	-1.784	10.1	30	0.745
Circuits 431-461, 586-588, 390-403 and 570-583 are added					
5	**457-498**	**-0.495**	**19.8**	**83**	**1.293**
	424-520	-3.027	7.6	7	0.933
	500-567	-1.665	10.9	21	0.774
No more circuits are added					

Fig. 8 shows output decrements due to transmission expansions are added to the Spanish system. These investments reduce exchange deviation about 15% and overload penalization about 30%. Additionally, the Spanish operation cost decreases about 1%. Scenarios of the Spanish system have been obtained sampling based on statistical behaviour at bidding and generation and transmission failure rates. The mean of unsupplied demand for this Spanish case has been zero for this specific case.

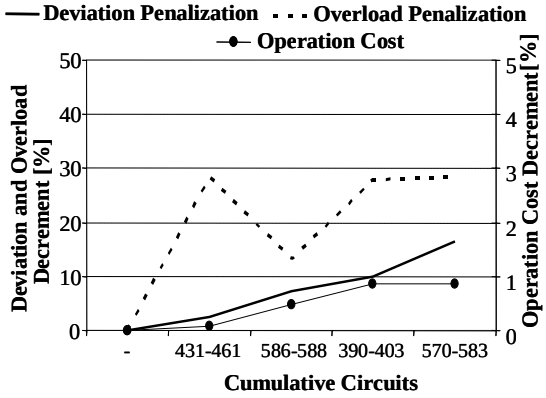

Fig. 8. Evolution on exchange deviations, overloads and cost

Implementation

The SO model has been implemented using GAMS modelling language combined with CPLEX 9.0. To obtain these analyses a Pentium IV 2.4 GHz has been used.

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