Probabilistic Midterm Transmission Planning in a Liberalized Market

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***Abstract*—This paper shows a midterm transmission planning methodology for liberalized electricity markets. This methodology evaluates expansions and reinforcements using a transmission adequacy linear programming model. This type of modeling solves efficiently, taking into account power exchange deviations, $n-1$ network preventive adequacy level, and nonsupply demand. Statistical results are obtained sampling power exchange scenarios and computing transmission investment sensitivities. After each sample of generation and consumption bidding and generator and circuit failures, means, ranges, and confidence intervals of transmission investment sensitivities are updated. These sensitivities are computed using dual variables and reduced costs of the transmission adequacy model. This statistical sensitivity information and additional information are evaluated jointly using multicriteria decision theory. An extended Garver's six-bus and the Spanish system cases are analyzed.**

***Index Terms*—Investment sensitivities, liberalized market, multicriteria decision theory, $n-1$ preventive criterion, transmission planning.**

NOTATION

THE notation used throughout this paper is classified as subscripts, constants, and variables.

A. Subscripts

b	Energy blocks.
c, i, j, m, n	Nodes.
h	Hours.
l, l'	Circuits.
t	Angle blocks.
u	Generators.
Ω	Set of bridge circuits.

B. Constants

g_l	Conductance of circuit l.
$k_{f,l}$	Reinforcement ratio of capacity increment versus capital investment on circuit l.
$k_{y,l}$	Expansion ratio of admittance increment versus capital investment on circuit l.
$k_{g,l}$	Expansion ratio of conductance increment versus capital investment on circuit l.
l_h	Network losses at hour h.
$m_{l,t}$	Loss slope of circuit l at block t.
$q_{u,h,b}$	Energy block submitted by generator u.
$q^0_{u,h,b}$	Cleared energy block of generator u.
$q_{c,h,b}$	Energy block submitted by consumer c.
$q^0_{c,h,b}$	Cleared energy block of consumer c.
$p_{u,h,b}$	Price block submitted by generator u.
$p_{c,h,b}$	Price block submitted by consumer c.
r_l	Resistance of circuit l.
v_c	Unserved energy penalization of consumer c.
w_l	Postfailure overload penalization of circuit l.
x_l	Reactance of circuit l.
$z_{i,j}$	Element (i,j) of the inverse of admittance matrix Z.
$\alpha_{l,l'}$	Flow sensitivity of circuit l after failure of circuit l'.
λ_h	Energy marginal price at hour h.
$\delta^{\max}_{l,t}$	Upper bound of angle block t of circuit l.

C. Variables

$Q_{u,h,b}$	Energy block by generator u to be cleared.
$Q_{c,h,b}$	Energy block by consumer c to be cleared.
$U_{c,h}$	Unserved energy of consumer c.
$\Delta G_{u,h,b}$	Upward power exchange deviation of generator u.
$\nabla G_{u,h,b}$	Downward power exchange deviation of generator u.
$\Delta O_{l,l',h}$	Positive overload of circuit l after failure of l'.
$\nabla O_{l,l',h}$	Negative overload of circuit l after failure of l'.
$F_{l,h}$	Lossless power flow of circuit l at hour h.
$R_{l,h}$	Ohmic losses of circuit l at hour h.
$\theta_{c,h}$	Voltage angle of node c at hour h.
$\delta_{l,h,t}$	Voltage angle of t-block of circuit l at hour h.

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], [2]. In liberalized generation markets, those previous objectives should be compatible with improving the efficiency of power exchanges among market participants [3]–[5]. Several European electric systems, such as the Spanish and England and 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 [6], [7]. As an alternative, this paper describes a method to determine transmission investments for improving power exchange efficiency in a liberalized generation market. This methodology simulates power exchange scenarios that are cleared by the

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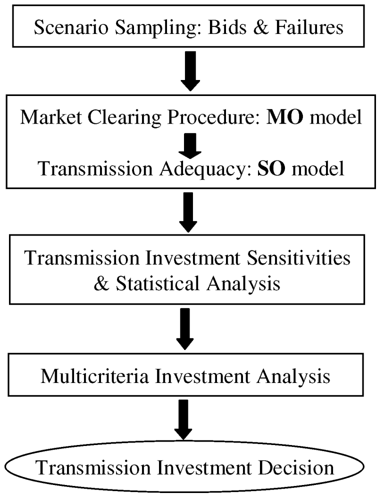

Fig. 1. Decision steps.

market operator (MO) using the MO model, and then, they are analyzed considering transmission adequacy criteria used by the system operator (SO).

According to the classification given by [8], this new transmission planning methodology can be classified as *mid term*, *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 uncertainty in the context of a liberalized market.

Transmission is modeled using a dc approximation including network losses [9]–[11], and system reliability is based on $n-1$ preventive adequacy criterion [12], by means of a linear programming model, the SO model. A transmission investment midterm plan is built based on consecutive decision stages whose basic steps are shown in Fig. 1.

This methodology is based on linear programming (LP) models to reduce its computational cost. Hundreds or thousands of impacts of transmission investments are simultaneously analyzed and due to sensitivities are computed using LP dual variables and reduced costs. Because of its high computational cost, integer and stochastic programming techniques are more appropriate to analyze long-term transmission expansion planning with a smaller number of system scenarios and network details [9], [13]–[15], [16].

Metaheuristic and heuristic solving techniques provide close to optimal solutions [17]–[19]. However, these techniques are not so computationally efficient because they should analyze one by one hundreds or thousands of possible expansions and/or reinforcements per scenario. Then, these techniques also require high computational cost, and in addition, they may converge to a local optimal solution.

This paper is divided into nine sections. Section I contains the notation used throughout this paper. Section II is this introduction section, Section III describes the scenario sampling mechanism, and Section IV shows the market clearing model (MO). The transmission adequacy model is described mathematically Section V. Transmission investment sensitivities are explained in the Section VI. In Section VII, the iterative procedure to rank transmission investments is described. In Sections VIII and IX, Garver's extended six-bus and the Spanish case analyzes are shown, respectively.

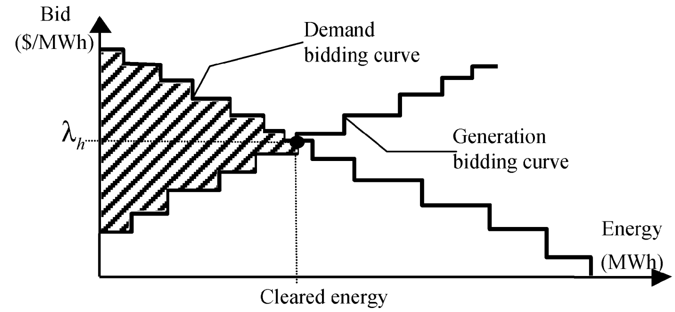

Fig. 2. Market operator matching procedure.

II. Scenario Sampling

Each system scenario contains a possible energy profile resulting from generator and demand bids, as well as a system availability status derived from generator and circuit failures. 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 conventional Monte Carlo method [20] has been used to sample system scenarios. Generation and network failures have been sampled using Bernoulli distributions adjusted, taking into account historical failure rates. Hydro and wind energy blocks are sampled using triangular probability distributions whose parameters are computed based on historical data analysis. Generation and demand block prices are sampled using a time-series structure containing tendency, cyclic, and random components. These components should be computed bearing in mind regional and international future economic and environmental analysis, fuel price forecasting and generation, and demand characteristics.

III. Market Clearing Model: The MO Model

On a daily basis, generators and consumers submit hourly bids to the MO, which clears them and after that, determines the hourly system marginal price to maximize social benefit among participants [21]. Then, selling and buying bids are exchanged at this marginal price. This section explains how this MO model has been implemented.

For each hour h, generator u 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 c submits $q_{c,h,b}$ energy blocks whose prices are noted by $p_{c,h,b}$.

The MO model maximizes the positive area between demand and generation bidding curves, as the dashed area in Fig. 2 shows. That maximization is formulated at the objective function

$$\text{Max} \sum_{c,b} p_{c,h,b} \cdot Q_{c,h,b} - \sum_{u,b} p_{u,h,b} \cdot Q_{u,h,b} \tag{1}$$

where $Q_{u,h,b}$ and $Q_{c,h,b}$ are the generators' and consumers' energy blocks variables whose optimal cleared values are noted by $q^0_{u,h,b}$ and $q^0_{c,h,b}$.

This model is based on a single node system model, where transmission losses estimation is considered as an additional demand. This previous objective function is subject to the energy balance between generation and consumption taking into account estimated network losses l_h

$$\sum_{u,b} Q_{u,h,b} = \sum_{c,b} Q_{c,h,b} + l_h \tag{2}$$

$$Q_{u,h,b} \leq q_{u,h,b} \tag{3}$$

$$Q_{c,h,b} \leq q_{c,h,b}. \tag{4}$$

Generators' and consumers' energy blocks are bounded by the submitted energy blocks (3), (4). The energy marginal price of hour h, noted by λ_h, is the highest price at which a demand energy block has been cleared. Other technical aspects, such as generators' ramp rates conditions, may be included into the previous formulation solving simultaneously several hourly consecutive MO problems.

IV. Transmission Adequacy Model: The SO Model

After solving the MO model, 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 power exchange deviations, nonfulfillment of network $n-1$ preventive criterion, and system unserved demand

$$\min \sum_{h,u} \sum_{b} (p_{u,h,b} \cdot \Delta G_{u,h,b} - \lambda_h \cdot \nabla G_{u,h,b}) + \sum_{h,l} \sum_{l'} w_l \cdot (\Delta O_{l,l',h} + \nabla O_{l,l',h}) + \sum_{h,n} v_c \cdot U_{c,h}. \tag{5}$$

Each component of this objective function has a different weight. 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 subtracted from the payment, 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 w_l. Nodal unserved energy $U_{c,h}$ is weighted by the v_c nodal penalty parameter.

The nodal energy balance equation, i.e., first Kirchoff law, is included into the SO model with the following equation:

$$\sum_{u \to c} \sum_{b} \left(q^0_{u,h,b} + \Delta G_{u,h,b} - \nabla G_{u,h,b}\right) + \sum_{l \to c} \left(F_{l,h} - \frac{1}{2} R_{l,h}\right) - \sum_{l \leftarrow c} \left(F_{l,h} + \frac{1}{2} R_{l,h}\right) = \sum_{b} q^0_{c,h,b} - U_{c,h};\ \forall c, h \qquad : \pi_{c,h}. \tag{6}$$

All generation units u at consumer node c, noted by $u \to c$, sum their cleared bids $q^0_{u,h,b}$ to their upward deviations and subtract downward deviations. Then, this generation power at node c is added to the transmission power inflows at node c.

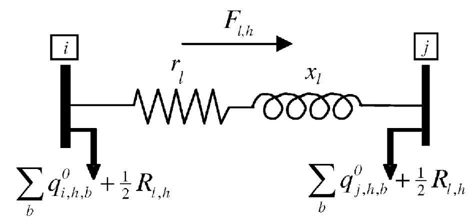

Fig. 3. Extended Π model of circuit l.

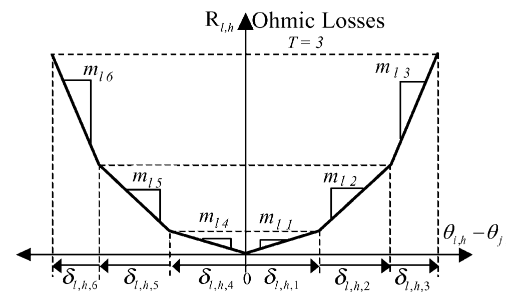

Fig. 4. Piecewise linear loss approximation.

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 c, noted by $l \to c$, add their net energy to the nodal balance and flows that come from node c, noted by $l \leftarrow c$, subtract their net energy at the equation. Ohmic losses at each circuit are modeled as demands at its extreme nodes (see Fig. 3). Those demands are subtracted from the lossless power flow. This nodal balance supplies the hourly demand unless unsupplied energy is set $U_{c,h}$. $\pi_{c,h}$ are dual variables of this balance equation that are used to compute transmission investment sensitivities.

Power flow of each circuit is computed using dc modeling, dividing voltage angle difference $(\theta_{i,h} - \theta_{j,h})$ by its circuit reactance x_l as follows:

$$F_{l,h} = \frac{(\theta_{i,h} - \theta_{j,h})}{x_l}, \ \forall l. \tag{7}$$

Circuit losses are approximated using a piecewise linear formulation

$$\theta_{i,h} - \theta_{j,h} = \sum_{t=1}^{T} \delta_{l,h,t} - \sum_{t=T+1}^{2T} \delta_{l,h,t} \tag{8}$$

$$R_{l,h} = \sum_{t=1}^{2T} m_{l,t} \cdot \delta_{l,h,t}. \tag{9}$$

This piecewise formulation divides circuit angle difference into $2T$ blocks (8) $\delta_{l,h,t}$, as Fig. 4 shows. These increments are multiplied by circuit slopes $m_{l,t}$ (9). Using this loss formulation, the SO model stays linear, so computationally, its solving process will be more efficient. As loss allocation function is convex and the objective function tries to minimize losses indirectly, angular increments are filled from the origin to one side direction, depending on the angular difference sign. Joint points of this approximation have been previously computed using a least-squares fitting procedure, depending on the number of angle blocks [10], [11]. Another way of defining this loss approximation consists of using an analytical expression for angular increment slopes, as in [9].

To implement transmission $n-1$ preventive criterion, every circuit failure is analyzed to determine postfailure overloads in other circuits. Some circuit failures, called *bridge circuits*, are excluded from this preventive analysis because they would isolate part of the system. Those circuits are included into the Ω set. The flow of circuit l after circuit l' failure is computed using network sensitivities $\alpha_{l,l'}$ [12]

$$\alpha_{l,l'} = \frac{\Delta F_l}{\nabla F_{l'}} = \frac{x_l}{x_{l'}} \cdot \frac{z_{m,i} - z_{m,j} - z_{n,i} + z_{n,j}}{x_{l'} - z_{m,m} + 2 \cdot z_{m,n} - z_{n,n}}, \quad \forall l \, \forall l' \notin \Omega. \tag{10}$$

These sensitivities determine the flow increment in circuit l when there is a decrement of flow in circuit l'. This expression contains elements of the inverse of admittance matrix Z and reactances of circuits x_l and $x_{l'}$. 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.

Postfailure flow of circuit l after the failure of circuit l' is divided into three components: $FP_{l,l',h}$, nonoverloaded 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

$$F_{l,h} + \alpha_{l,l'} \cdot F_{l',h} = FP_{l,l',h} + \Delta O_{l,l',h} - \nabla O_{l,l',h}, \quad \forall l. \tag{11}$$

Bounds of SO variables are

$$0 \le \Delta G_{u,h,b} \le q_{u,h,b} - q^0_{u,h,b} \tag{12}$$
$$0 \le \nabla G_{u,h,b} \le q^0_{u,h,b} \tag{13}$$
$$0 \le U_{c,h} \le \sum_b q^0_{c,h,b} \tag{14}$$
$$-F_l^{\max} \le F_{l,h} \le F_l^{\max} : \pi_{F_{l,h}} \tag{15}$$
$$-F_l^{\max} \le FP_{l,l',h} \le F_l^{\max} : \pi_{FP_{l,h}} \tag{16}$$
$$0 \le \Delta O_{l,l',h}, \, \nabla O_{l,l',h} \le \infty \tag{17}$$
$$-\frac{\pi}{2} \le \theta_{c,h} \le \frac{\pi}{2} \tag{18}$$
$$0 \le \delta_{l,h,t} \le \delta^{\max}_{l,t}. \tag{19}$$

These bounds 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 original bids and cleared bids $q_{u,h,b} - q^0_{u,h,b}$(12). Negative generation deviations are limited by the cleared bid $q^0_{u,h,b}$ (13). Unserved demand is limited by the blocks of the cleared demand bid (14).

Non-overloaded prefailure and postfailure flows are limited to the circuit capacity $F_l^{\max}$ (15), (16). Their reduced costs $\pi_{Fl,h}$ and $\pi_{FPl,h}$ are used to compute transmission reinforcement sensitivities. Overloaded ranges of postfailure flows are unlimited in both directions (17). Voltage angles are limited to $\pm\pi/2$ radians (18). Bounds on circuit angle blocks (19) are previously obtained by a least-squares fitting procedure.

Finally, the SO programming model uses the objective function (5) subject to constraints defined by (6)–(19), excluding network sensitivities expression (10). This model has been implemented using GAMS modeling language [24] combined with CPLEX 9.0.

V. Transmission Investment Sensitivities

Transmission investments are classified as reinforcements (uprating existing circuits) and expansions (new circuits or transformers). Investment sensitivities (ISs) provide marginal information about improvements in the objective function versus capital investments on transmission. Focused on each IS, the lower negative value is that the better system power exchange performance is achieved if that investment is done. Based on the LP post-optimal information, IS are computed using dual variables and reduced costs of the SO model.

A. IS of Circuit Reinforcements

Reinforcements make the assumption that the increment of the capacity of circuit l $\Delta F_l^{\max}$ is proportional to the capital investment ΔI_l [22]. That capacity ratio is noted by $k_{f,l}$

$$k_{f,l} = \frac{\Delta F_l^{\max}}{\Delta I_l}. \tag{20}$$

Besides, reinforcements assume that electric parameters of reinforced circuits are fixed. To compute circuit reinforcement sensitivities ρ_l, reduced costs of bounds (15) and (16) π_{Flh} and π_{FPlh} are used

$$\rho_l = \frac{\Delta \text{obj. function}}{\Delta I_l} = \frac{\Delta o.f.}{\Delta F_l^{\max}} \cdot \frac{\Delta F_l^{\max}}{\Delta I_l} = \left(\pi_{F_{l,h}} + \pi_{FP_{l,h}}\right) \cdot k_{f,l}. \tag{21}$$

B. IS of Circuit Expansions

These new circuits or transformers assume a direct proportion $k_{y,l}$ between new circuit admittance y_l and capital investment I_l and also another proportion $k_{g,l}$ between new circuit conductance g_l and capital investment I_l

$$k_{y,l} = \frac{y_l}{I_l} \tag{22}$$
$$k_{g,l} = \frac{g_l}{I_l}. \tag{23}$$

To enhance IS accuracy, after solving the SO model, transmission losses are evaluated using a more accurate nonlinear expression instead of using the previous piecewise linear approximation

$$R_{l,h} = 2 \cdot g_l \cdot \left[1 - \cos(\theta_{i,h} - \theta_{j,h})\right]. \tag{24}$$

Dual variables of constraint (6) $\pi_{n,h}$ are used to evaluate expansion sensitivities γ_l

$$\gamma_l = \frac{\Delta \text{obj.function}}{\Delta I_l} = \frac{\Delta o.f.}{\Delta y_l} \cdot \frac{\Delta y_l}{\Delta I_l} + \frac{\Delta o.f.}{\Delta g_l} \cdot \frac{\Delta g_l}{\Delta I_l}$$
$$= (\pi_i - \pi_j) \cdot (\theta_i^0 - \theta_j^0) \cdot k_{y,l} + (\pi_i + \pi_j) \cdot \left[1 - \cos\left(\theta_i^0 - \theta_j^0\right)\right] \cdot k_{g,l}. \tag{25}$$

These expansion sensitivities use voltage angle on extreme nodes i and j of the new circuit l, $\theta_i^0 \, y \, \theta_j^0$. This expression is based on dual variables of the SO model evaluating the simultaneous impact of changing admittance and conductance of a new circuit.

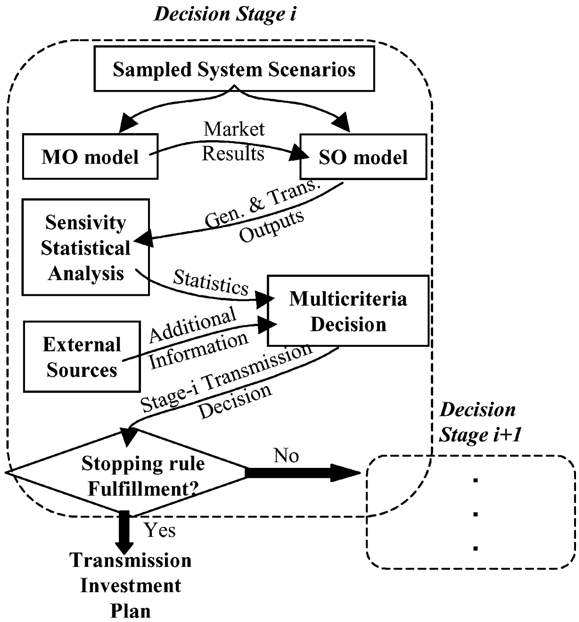

Fig. 5. Investment decision stages.

C. IS of Expansions With Isolated Nodes

Expansions that connect isolated nodes to the system uses capacity, admittance, and conductance ratios of new circuits. The IS expression changes slightly

$$\gamma_l = \frac{\Delta \text{obj.function}}{\Delta I_l} = (\pi_i - \pi_j)\cdot k_{f,l} + (\pi_i + \pi_j)\cdot \left(1 - \cos\left(\frac{k_{f,l}}{k_{y,l}}\right)\right)\cdot k_{g,l}. \quad (26)$$

D. Validity Ranges of IS

This type of range sets the transmission capacity increment for which an IS value remains the same. Those ranges are computed as the minimum *right-hand size range* of the dual variables of constraints (6) and the reduced costs of variables whose upper and lower bounds are given by (16) and (17). This information is provided by the CPLEX optimization solver and expressed in megawatts.

VI. Transmission Investment Midterm Planning

This transmission investment planning provides a set of consecutive expansions and/or reinforcements to add to the network for midterm horizon, typically from one to five years. This investment set is obtained, completing several decision stages whose steps are depicted in Fig. 5.

At each stage, a different collection of sampled system scenarios is evaluated by the MO model obtaining market results, such as marginal prices and generation and demand cleared energy blocks. Those MO results and the same sampled scenarios are analyzed by the SO model to provide generation and transmission outputs, such as power exchange deviations, power flows, dual variables, and reduced costs.

Then, SO results are used to update IS statistics (means, confidence intervals, and validity ranges). Then, these statistics are included into a multicriteria decision procedure with additional information coming from external sources to provide the best transmission investment decision per stage. Finally, that investment decision is added to the network, and its impact on the SO model is used as stage stopping criteria. In case of nonfulfillment of stopping rule, an additional decision stage is done.

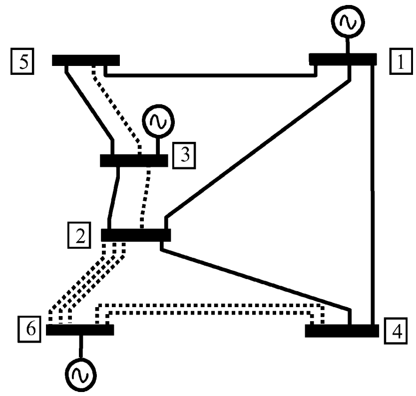

Fig. 6. Original and expanded Garver's system.

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

VII. Garver's Study Case

Original Garver's six-bus system [23] (see the solid lines in Fig. 6) has been extended with bidding data for generators and consumers. Generators' hourly energy bids are shown in Table I. Uncertainty on generation prices has been modeled using a normal distribution whose mean value is in Table I and a standard deviation of $5/MWh. Negative sampled prices are truncated to zero price. Consumers' hourly energy bids are shown in Table II. These consumption values are modeled as fixed. 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 [9]. No transmission reinforcements have been included in this analysis.

For each decision stage, 1000 scenarios are sampled, and after using a multicriteria decision process, a transmission investment is added to the network of Garver's system. Seven consecutive decision stages are detailed in Table IV. The three best candidates per stage are shown in the second column. The bold one

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

TABLE IV
CONSECUTIVE INVESTMENT DECISION STAGES

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					
No more decisions stages are done					

is the chosen expansion. Then, sensitivity means and their confidence intervals, expressed in percentage, are depicted in the third and fourth columns. The fifth column shows means of validity ranges. The last column shows the multiattribute value for each expansion at each stage.

For each decision stage, this multiattribute value is computed in two steps. The first step consists of dividing each type of output by the mean of the best three values obtaining ratios around one. The second step consists of weighting those type of ratios according to the impact on the SO model objective function. The SO objective function is affected by the product of sensitivity means and validity ranges, so both should have the same weight (e.g., 45%). Confidence intervals have less importance than sensitivities values, so their weight should be lower (10%).

Original and expanded Garver's system are illustrated in Fig. 6. 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. These expansions decisions are similar to the solution obtained by other authors using nonprobabilistic integer programming (NPIP) model [9], as Table V shows.

TABLE V
GARVER'S RESULTS COMPARISON

Corridor	Number of lines built	
	NPIP Model [9]	**Probabilistic model**
2-6	2	3
4-6	2	2
3-5	1	1
2-3	0	1

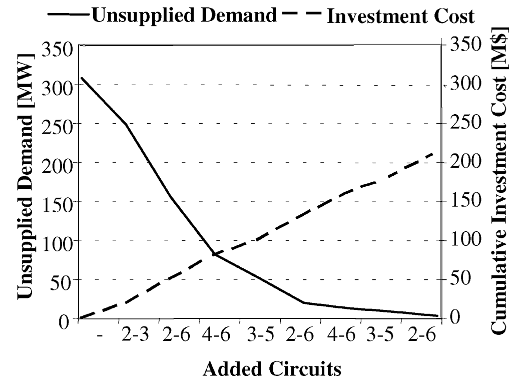

Fig. 7. Garver's unsupplied demand and investment cost.

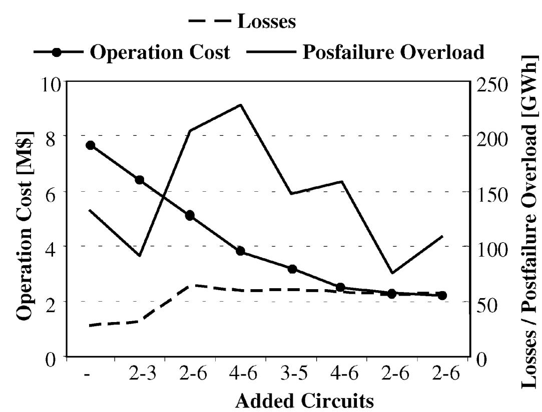

Fig. 8. Operation results evolution versus added circuits.

Fig. 7 shows that 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 having similar individual investments.

Fig. 8 shows that the system operation cost decreases to a M$2 as the number of circuits increases. This system operation cost consists of the SO objective function, taking into ac-

TABLE VI
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					
4	**570-583**	**-0.587**	**51.4**	**129**	**1.434**
	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					
No more decision stages are done					

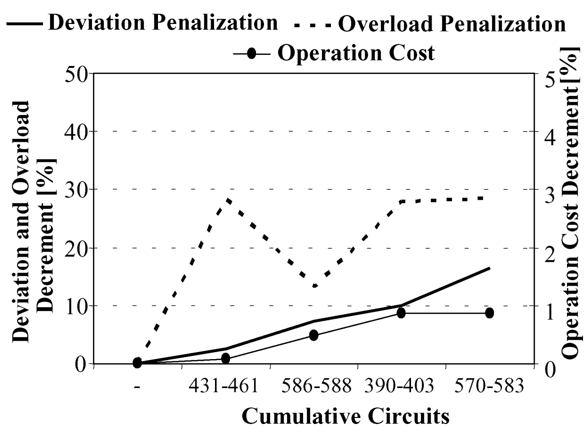

Fig. 9. Evolution on exchange deviations, overloads, and cost.

count penalizations due to exchange deviations, preventive network overloads, and unserved demand. Improvement on operation cost is set as stopping rule of new decision stages.

First Garver's expansions diminish unserved system demand because of energy flows through the network increase. However, the higher the network flows, the more postfailure overloads and transmission losses exist. Nevertheless, after the first three expansions, output improvements are smaller. After seven transmission expansions, improvements on operation cost are practically zero.

VIII. SPANISH STUDY CASE

The Spanish case has been analyzed by this methodology. This big-size case contains 623 nodes and 1021 circuits, 165 thermal groups, and 76 hydro units. For each decision stage, 100 scenarios are analyzed, and in Table VI, the three best expansion choices are shown. The multicriteria value has been obtained weighting as in Garver's case. The best transmission expansion for each stage is consecutively added to the system.

Fig. 9 shows output evolutions due to transmission expansions that are added to the Spanish system. These expansions reduce exchange deviation about 15% and overload penalization about 30% from the initial value. Additionally, the Spanish operation cost decreases about 1%. Scenarios of the Spanish system have been obtained, sampling based on historical bidding behavior and generation and transmission failure rates. The mean value of unsupplied demand for this Spanish case has been zero. No more circuits are added, due to the very small operation cost improvement.

IX. CONCLUSION

This paper has detailed a midterm transmission planning methodology for liberalized generation markets. LP modeling has been used to increase computational efficiency. These outputs are evaluated statistically after sampling energy biddings and system availabilities. Sensitivities on transmission investments are computed based on post-optimization results to evaluate simultaneously multiple expansions and reinforcements. Consecutive multicriteria decision stages provide a transmission expansion plan. Small- and big-size cases have been analyzed to illustrate the implementation of this methodology.

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