A FUZZY APPROACH TO POWER SYSTEM PLANNING AND POWER TRANSACTIONS IN A COMPETITIVE ENVIRONMENT

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ABSTRACT - The deregulation of the electricity industry places a number of complex questions related namely with planning and operating activities. In this paper one will enumerate some of these issues and give an overview about the way this process is being handled in several countries. In the paper one will also describe a methodology to identify the most adequate components to be reinforced considering that one aims at reducing the risk felt by the planner if loads are modeled by fuzzy numbers. At the end, fuzzy concepts are integrated in a model to validate from a technical point of view a set of trades established between electricity buyers and sellers in a competitive environment.

1. INTRODUCTION

In recent years power systems are facing new challenges that are related to structural changes of the main principles concerning planning and operation activities. These changes are included in a more general trend that has already affected areas as telecommunications and airlines. These activities went through a deregulation process that started in the 80th and that virtually substituted large and frequently uncompetitive monopolies by several entities competing in an open market. This process was conceived to provide best services at lower costs to clients. Indeed, it also implied a change in the user's way of thinking. In fact, users now have in different fields several alternatives from which they have to select the best one according to their needs. This implies a more cautious standing and a wider access to information about the available services.

Electric utility industry went through the last decade almost immune to this movement. It was only by the end of the 80th that some steps were adopted in some Latin-American countries and in the U.K. More recently, other European countries (Finland and Sweden, for instance) and some USA states (as California) moved in this direction. This movement started by dismantling the vertically integrated utilities and substituting them by a larger set of entities participating in the market. The liberalization of the generation subsystem, the adoption of policies to stimulate the use of co-generation, wind or small hydro resources can also be included in this general movement towards market. As a consequence of this process the non-utility owned new installed capacity, for instance, in the USA increased from 16% in 1985 to 64% in 1992.

However, the development of an open electricity market is much more complex than in other areas. In fact, the operation of power systems is subjected to a large set of constraints related not only with technical limits of components but also with security requirements of the systems. Therefore, consumers and generator owners will not be able to establish contracts for buying/selling energy without subjecting them to a technical validation. This process is designed to make sure that none of the previous constraints are violated.

In section 2 of this paper we will address the problems and challenges of the deregulation process as well as the experiences available in several countries in this area. In section 3 a power system planning methodology designed to identify the most adequate components to be reinforced will be described. It integrates in a novel way probabilistic information describing the life cycle of components and the uncertainty in loads modeled by fuzzy numbers. In section 4 we present a model to validate from a technical point of view a set of bilateral buying/selling power trades. This model will also integrate fuzzy membership functions to represent the satisfaction degree felt by generator owners regarding the profit they get. In section 5 results from case studies using these models are presented and in section 6 the most relevant conclusions will be drawn.

2. THE MOVE TOWARDS COMPETITION

As referred in section 1 the operation of an electricity market creates several new problems. In this scope, one can refer:

- the increased difficulty to undertake power system planning activities as power flows will depend on the market, that is, on the price and amount of energy offered and required by sellers and buyers. Therefore, the traditional planning activities will have to be, at least, adapted to the new environment;
- models should be able to integrate uncertainties represented not only by probabilistic models, but also inherent to linguistic declarations available from experts. This type of subjectivity can be adequately modeled by Fuzzy Set Theory [1];
- reliability and service quality requirements will also be a major task as it must be defined who will pay, for instance, for an expansion of the transmission system if reliability reaches unacceptable levels. This also arises another important question. In fact, one clearly feels the need for an independent entity responsible, for instance, for evaluating the reliability of the system;
- power losses in the transmission system must also be

assigned and paid by those using the transmission grid. This question is, however, a complex one so that it was not taken in account in some countries were a deregulated system is already implemented. In this scope, several cost notions were proposed to build transit tariffs. In [2], several approaches integrating marginal costs are used to build tariff systems;

Therefore, it is not a surprise that new computational tools to support market activities are under development. In [3] a crisp formulation to model energy transactions in a market environment is presented while in [4] the Chilean experience on marginal pricing of electric transmission systems is described. At last, reference [5] describes a crisp formulation to optimize sale transactions in a market environment using a lagrangean relaxation approach.

In USA this deregulation process is also under discussion. The move began in 1978 after the "Public Utility Regulatory Policy Act - PURPA" was passed. This law ended with a monopolist type of organization of Power Systems as new generation facilities were admitted - Qualifying Facilities. In 1992 the "Energy Public Act - EPA" strongly changed the main principles that were directing the operation of Power Systems as concepts as competition and energy market were in the front line. Anyway, one can find USA states were this process is more advanced when compared with what occurs in others.

As referred before, the changes started in the generation subsystems. However, nowadays, much attention is being paid to the transmission area as one clearly feels that a competitive energy market can not be established unless the transmission network is opened and, in fact, unless its operation is restructured. The discussion about how "Open Access" to the transmission network can be done is not yet completed since two models were proposed - the "Pool" model and the "Coordinated Multilateral Trade" model. In the second model buyers and sellers compete in the open market to establish the most interesting contracts in terms of price and, eventually, of other technical conditions. In a second phase, these non coordinated contracts will have to be analysed to check if generations and consumptions are feasible regarding the technical and security constraints of the network. Therefore, there must be an entity in charge of this technical, rather then commercial, validation. In the "Pool" model, electricity buyers and sellers communicate to a "Super-Entity" their offers. This "Super-Entity" becomes the responsible for market-making and for services as tariffs, spinning reserve and security monitoring.

3. A PLANNING METHODOLOGY USING FUZZY SETS

3.1. General Considerations

Power system planning models usually integrate probabilistic concepts either to represent the life cycle of components or to model the uncertainty about load values. This approach may be questioned as one feels that in planning studies it is also important to integrate knowledge expressed by linguistic declarations provided by experts. In fact, probabilistic distributions are valid when one has a large amount of events that fully characterize the behavior of the system. If we are dealing with the future one may ask if the general laws governing the evolution of the power system will keep unchanged. If that is not true, probabilistic distributions are not so adjusted to represent that kind of uncertainty. That is why for several years from now several efforts were developed to integrate information modeled by fuzzy sets in power system models.

As an example, in [6] an AC fuzzy power flow model is presented and in [7] a DC Fuzzy Optimal Power Flow - FOPF algorithm is developed. In these algorithms loads are represented by fuzzy trapezoidal numbers and we aim at reflecting this uncertainty on the results usually obtained by power flow or optimal power flow studies.

When performing a FOPF study we aim at identifying a generation policy that minimizes the cost subjected to a number of constraints. However, due to the current system topology or the generation or branch limits, a non zero Power Not Supplied - PNS - value can come as output. In this case the system is no longer able to accommodate all the specified uncertainty since at least one system component imposes a bottleneck on the credibility levels of load combinations for which PNS is still zero.

This reasoning suggests that components responsible for those bottlenecks should be reinforced. At this stage one must remember that, due to the non ideal nature of components, it is not enough to study only one system state. In fact, a reinforcement that is interesting to increase the ability of a state to accommodate more uncertainty may prove to be inappropriate for other states. That is why one must keep a global vision of the system behavior that can be obtained by sampling a large number of system states in the scope of a Monte-Carlo simulation. In the application described in [8] each state is analysed by running a FOPF exercise It is important to stress that in this simulation we will only sample the availability of system components as load uncertainties are represented and treated as a whole by fuzzy numbers.

3.2. Sampling And Analysis Of States

The states to be analysed are sampled using the Forced Outage Rates of components. This process is performed in an non chronological way by simply comparing sequences of pseudo-random numbers with the referred FORs.

As referred each sampled state is analysed by running a FOPF exercise. The solution strategy described in [7] to solve this problem integrates the following main steps:

- in the first place one formulates a linear programming problem in which one aims at identifying the generation policy that minimizes the production cost according to a number of constraints: the balance generation/load equation, the generation and the branch flow limits. This problem also integrates variables to represent the Power Not Supplied - PNS. A large cost is assigned to them to make sure that they will enter in the basis only if feasibility can not be obtained other way. This initial crisp linear programming problem is solved for the central values of the specified load membership functions. This will lead to an optimal and feasible crisp solution of the problem;

- in the second place, one will take into account load uncertainties by associating a parameter to the 0.0-cut of each load membership function. A multiparametric optimization problem is, thus, formulated. Gal [9] presented a methodology to identify regions related to feasible and optimal solutions that has, however, a rather poor computational performance for real sized problems. Therefore, an efficient alternative procedure was adopted;
- this procedure identifies vertices of the hypervolume enclosing the specified uncertainties according to very simple rules that are detailed in [7];
- for each of these vertices, it is performed a parametric linear programming study to identify solutions for load combinations varying from the set of central points of the load membership functions to the combination of extreme points of their 0.0-cut related to the vertex under analysis. As a result one gets partial membership functions for generations, branch flows and PNS;
- finally, the fuzzy union operator proposed by Zadeh [1] is used to merge these partial membership functions.

3.3. Risk Indices

The algorithm sketched in 3.2 also outputs the lowest level of uncertainty, that is the lowest α-cut, for which the system still has capacity to accommodate all the specified load uncertainties. For uncertainty levels lower than α one or more components impose bottlenecks that lead to non zero PNS values. For sake of clarity let us consider the PNS membership function depicted in figure 1. The value α_1 corresponds to the Exposure Index of the system and the value 1.0 - α_1 is denoted as Robustness Index. In this sense the system is robust for load levels not lower than α_1 since for any combination of loads with membership degree higher than α_1 a DC-OPF gives a zero value for PNS.

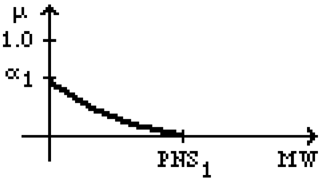

Fig. 1 - Example of PNS membership function.

3.4. Aggregation Of Results

For each state i analysed, the previous algorithm gives the values of the Robustness and Exposure Indices and the PNS membership function, $Irob_i$, $Iexp_i$ and PNS_i. These values can be aggregated using (1 to 3) in order to obtain estimates of the their expected values.

$$E(Irob) = \frac{1}{N} . \sum_{i=1}^{N} Irob_i \quad (1)$$

$$E(I\exp) = \frac{1}{N} . \sum_{i=1}^{N} I\exp_i \quad (2)$$

$$E(PNS) = \frac{1}{N} . \sum_{i=1}^{N} PNS_i \quad (3)$$

3.5. Convergence Monitoring

The convergence of the Monte Carlo simulation is monitored by calculating the uncertainty coefficient (4). In this expression, E(PNS) is the current estimate of PNS expected value obtained using the sample of PNS crisp values calculated in the first phase of FOPF. V(PNS) is the variance of this sample. The simulation ends when the calculated β gets inferior than the specified target.

$$\beta^2 = \frac{V(PNS)}{N.(E(PNS))^2} \quad (4)$$

3.6. Building A List Of Reinforcements

3.6.1. From Candidate To Credible Reinforcements

A reinforcement strategy may include the simultaneous expansion of several components. Besides, one also realizes that the same reduction of Iexp can be obtained by adopting different strategies. An initial Monte Carlo simulation where the values of the dual variables related to the constraints of the problem that reached their limit is used to obtain indications about the potential of each reinforcement to reduce Iexp. The analysis of the strategies identified this way will be performed in a more deep way in a second Monte Carlo simulation. This second exercise will be used to identify for each sampled state the required capacity expansion of each component integrated in that strategy and the increase in Iexp. The quality of an expansion strategy depends on the number of states in which that strategy successfully allows the reduction of Iexp to, at least, the target value. That is why a statistical index is proposed to quantify the goodness of each strategy.

Once a list of candidate strategies is built one will run a Monte Carlo simulation. The initial DC-OPF study and the parametric problems referred in 3.2 are now formulated considering that there will not be variables representing PNS. In fact we are interested in evaluating each expansion strategy without disconnecting load. The constraints related to generation and branch flow limits also integrate variables to represent the expansions in the strategy being analysed.

As a result of this simulation one gets the reinforcement values for the components integrated in each strategy so that the target Iexp is obtained. If this target is not reached, bottlenecks in other components of the system are not overcome by the strategy in analysis.

3.6.2. Statistical Index

The goodness of a reinforcement strategy k is evaluated monitoring the uncertainty coefficient of an Indicator Function I(x). This function is 1.0 if the Iexp of state x is reduced, at least, to the target value. The 0.0 value means that the target was not reached. Let us consider that in N_c of N sampled and analysed states Iexp was higher than the desired one. Among these N_c states, strategy k is able to reduce Iexp to, at least, the target in N_1 states, that is, in N_1 states I(x) is 1.0. In $N_0=N_c-N_1$ function I(x) is 0.0. The expected value and the variance of I(x) are given by (5) and (6). The uncertainty coefficient (7) statistically measures the ability of reinforcement strategy k to overcome the bottlenecks detected in a larger or smaller number of states.

$$E(I)=\frac{N_1}{Nc} \quad (5)$$

$$V(I)=\frac{1}{N_c-1}.(N_1.(1-E(I))^2+N_0.(E(I))^2) \quad (6)$$

$$(\beta_I^k)^2=\frac{V(I)}{N_c.(E(I))^2} \quad (7)$$

3.6.3. Final Trade-Off Analysis

The indications obtained from this Monte Carlo exercise can be organized in a way suited to perform a Trade-Off analysis between the cost of implementing each strategy and the reduction of the E(Iexp). This analysis can be conducted eliminating, in a first phase, the dominated strategies and selecting, in a second one, the most adequate strategy considering the trade-off between the investment and the reduction of E(Iexp).

4. TECHNICAL VALIDATION OF TRADES IN A COMPETITIVE ENVIRONMENT

4.1. General Considerations

Let us consider a power system that is operated in a market environment. In this scope, generator owners and consumers can establish trades directly between them or they may convey their buying/selling offers to a broker. These trades should be profitable meaning that (8) should hold considering that generator owner gets a profit from delivering a power P to a consumer since the money he gets from the consumer - cl - is higher than the total cost of generation - cg. In a market environment the generator owners tend to establish trades with the consumers that are able to pay more for the same power, and the consumers try to make trades with cheaper generators.

$$cl(P) \geq cg\,(P) \quad (8)$$

A set of non-coordinated trades between generators and consumers may not be valid since power systems have a large number of constraints that must not be violated - technical, security and power flow constraints. Therefore, these trades must be validated from a technical point of view and eventually changed if necessary.

4.2. Algorithm Integrating the DC Model

Let us consider, without loss of generality, that in each bus there is a generator and a load. $P^o{}_{gij}$ represents the power generated in bus i and delivered to bus j according to the initial trades established between generator owners and consumers. ΔP_{gij} represents the deviations of those powers as an output of the technical validation study to be performed. According to this notation, let us define $Prf^o i$ and $Prf^1 i$ (9 and 10) the profits of generator i evaluated before and after the technical validation study.

$$Prf^o i = \sum cl(P^o{}_{gij}) - cg(\sum P^o{}_{gij}) \quad (9)$$

$$Prf^1 i = \sum cl(P^o{}_{gij}+\Delta P_{gij}) - cg(\sum P^o{}_{gij}+\sum \Delta P_{gij}) \quad (10)$$

The technical validation study aims at correcting, if necessary, the trade policy diminishing profits of each generator the least it is possible. This leads to a membership function for the profit as sketched in fig. 2. According to this figure, profits not inferior than $Prf^o i$ completely satisfy the owner of generator i. Profits inferior than $(1-\varepsilon).Prf^o i$ (where ε is a tolerance expressed as a number in [0.0;1.0]) completely dissatisfy that owner. Values between these two extreme situations have a membership degree of μ.

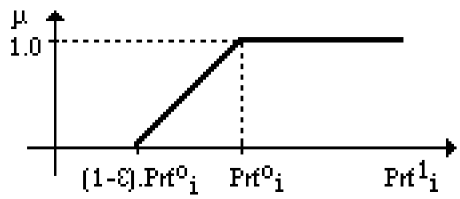

Fig. 2 - Membership function of the profit $Prf^1 i$.

According to this reasoning, in the technical validation study one aims at maximizing the satisfaction felt by generator owners, that is, one wishes to maximize the membership degree μ. Therefore, the technical validation model is formulated according to (11 to 18).

$$\max \quad z = \mu \quad (11)$$

$$\text{subj.} \quad \sum\sum (P^o{}_{gij} + \Delta P_{gij}) = \sum P_{Lj} \quad \text{(for each load j)} \quad (12)$$

$$P_{gi}{}^{min} \leq \sum P^o{}_{gij} + \sum \Delta P_{gij} \leq P_{gi}{}^{max} \quad \text{(for each generator i)} \quad (13)$$

$$-P_k{}^{max} \leq \sum a_{ki}\,(\sum P^o{}_{gij} - P_{li} + \sum \Delta P_{gij}) \leq P_k{}^{max} \quad \text{(for each branch k)} \quad (14)$$

$$0 \leq P^o{}_{gij} + \Delta P_{gij} \leq P_{lj} \quad \text{(for each i and each j)} \quad (15)$$

$$Prf^1{}_i \geq (1-\varepsilon).Prf^o{}_i + \mu.\varepsilon.Prf^o{}_i \quad \text{(for each generator i)} \quad (16)$$

$$0.0 \leq \mu \leq 1.0 \quad (17)$$

$$\Delta P_{gij} \in \Re \quad (18)$$

In these expressions:

- P_{Lj} is the load connected to bus j;
- P_{gi}^{min} and P_{gi}^{max} are the limits of generator i;
- a_{ki} are the sensibility coefficients as established by the DC power system model;
- P_k^{max} is the maximum power flow in branch k;

In this formulation equations (12) (one for each load) correspond to a decoupled version of the load/generation balance equation to ensure that all loads are supplied. Constraints (13) and (14) impose limits on generations and branch flows. Constraints (15) correspond to limits on power that is traded between each generator and each consumer, while (16) represents the lower bound - integrating the tolerance ε - imposed on the profits of each generator i.

4.3. Algorithm Integrating an AC Model

Using the same notation, the problem to maximize the satisfaction felt by generator owners is now given by (19 to 21). Constraints (20) represent the power flow equations while (21) represent the technical limits of components, security constraints and bounds on traded powers and on profits. These constraints can be expressed in terms of bus voltages and phases - X -, traded powers - $P^o{}_{gij}$, ΔP_{gij} - and other control variables as reactive powers.

$$\max \quad z = \alpha \quad (19)$$

$$\text{subj} \quad g(X, P^o{}_{gij}, \Delta P_{gij}, U) = 0 \quad (20)$$

$$h(X, P^o{}_{gij}, \Delta P_{gij}, U) \leq 0 \quad (21)$$

5. RESULTS FROM CASE STUDIES

5.1. Results From a Planning Exercise

The methodology described in section 3 will be exemplified using the results obtained from a case study based on the IEEE 24 bus network. Regarding this network one specified trapezoidal fuzzy numbers to model loads (uncertainty of +10% and -10% at level 0.0 and +5% and -5% at level 1.0, around the corresponding central value). A first Monte Carlo simulation gives a value of 0.303 for the E(Iexp). Afterwards, a second Monte Carlo simulation was run using the methodology described in section 3 in order to evaluate the goodness of the fifteen reinforcement strategies listed in table 1 considering that Iexp should be reduced as much as possible. The results obtained are summarized in table 1.

strategy	branch	N_1	N_0	Max. reinf.	E(Iexp)	$\beta_I{}^k$
number	or gen.			(MW)		
1	2/4	220	133	725.0	0.102	0.041
2	1/4	211	141	725.0	0.106	0.044
3	23/3	168	195	1190.0	0.154	0.057
4	13/3	111	204	725.0	0.159	0.076
5	14-16	124	246	225.0	0.208	0.073
6	7-8	105	271	190.0	0.217	0.083
7	6-10	88	293	45.0	0.231	0.094
8	21/1	14	299	1165.0	0.229	0.261
9	18/1	11	296	655.0	0.237	0.296
10	15/6	26	333	945.0	0.241	0.189
11	16/1	28	334	720.0	0.249	0.182
12	7/3	5	360	720.0	0.276	0.444
13	22/6	8	368	125.0	0.293	0.372
14	10-12	3	378	105.0	0.302	0.575
15	12-13	3	376	25.0	0.302	0.575

Tab. 1 - Results regarding the goodness of 15 strategies.

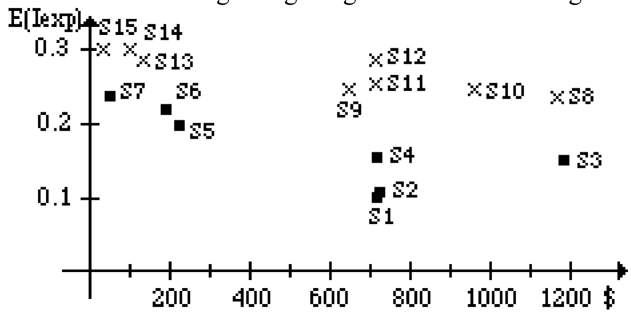

Fig. 3 - Trade-off analysis of the reinforcement strategies:

• - strategies with $\beta_I{}^k$ less than 10%.

x - strategies with $\beta_I{}^k$ higher than 10%.

As an example, the first strategy listed in table 1 corresponds to expand the capacity of generator 4 connected to bus 2. Its expansion reduces Iexp to 0.0 in 220 states while in 133 other states one still gets non zero PNS values. Therefore, E(Iexp) is reduced to 0.102 considering an expansion of 725.0 MW of this generation capacity. This strategy has a $\beta_I{}^k$ value of 4.1%.

The results presented in this table for E(Iexp) and the investment related to each expansion are sketched in figure 3. Considering the didactic purposes of this study, a 1.0$/MW was assumed for all reinforcements. Among the strategies having $\beta_I{}^k$ less than 10%, one can conclude that S2, S3 are S4 dominated ones. The planner should select a strategy in the set integrating S1, S5, S6 and S7 taking in account the trade-off he is prepared to assume.

5.2. Technical Validation of Trades

Let us consider the network sketched in fig. 4. This is a toy network that is used here only for didactic purposes in order to exemplify the proposed trade validation model. In tables 2 and 3 one includes node and branch data of the system. (22 to 25) are the generator cost functions and (26 to 29) are the functions giving the amount to be paid by each load.

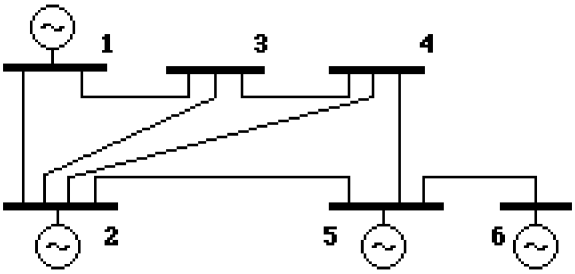

Fig. 4 - Toy network to illustrate the validation algorithms.

node	Pg^{max} (MW)	Load (MW)
1	110.0	--
2	100.0	20.0
3	--	45.0
4	--	40.0
5	10.0	60.0
6	10.0	--

Tab. 2 - Node data.

node i	node k	x(pu)	Pij^{max} (MW)
1	2	0.06	40.0
1	3	0.24	50.0
2	3	0.18	50.0
2	4	0.18	50.0
2	5	0.12	50.0
3	4	0.03	50.0
4	5	0.24	50.0
5	6	0.03	15.0

Tab. 3 - Branch data.

$$cg(P_{g1}) = 5.P_{g1} + 0{,}02.(P_{g1})2 \quad (22)$$
$$cg(P_{g2}) = 4.P_{g2} + 0{,}03.(P_{g2})2 \quad (23)$$
$$cg(P_{g5}) = 3.P_{g5} + 0{,}025.(P_{g5})2 \quad (24)$$
$$cg(P_{g6}) = 4.P_{g6} + 0{,}02.(P_{g6})2 \quad (25)$$
$$cl(P_{l2}) = 6.P_{l2} \quad (26)$$
$$cl(P_{l3}) = 12.P_{l3} \quad (27)$$
$$cl(P_{l4}) = 10.P_{l4} \quad (28)$$
$$cl(P_{l5}) = 11.P_{l5} \quad (29)$$

In table 4 we include the power values to be supplied to each load as defined by the initial trades. A power flow exercise using the DC model would reveal that the flow in branch 1-2 (73.94 MW) exceeds its limit. Therefore, the model presented in section 4.2 is used to alter these trades. For this exercise, we admitted a tolerance of 30% on the profits obtained by the generators calculated for the initial trades. Just to stress the flexibility of the model we also considered that the trades involving consumer 2 should not be altered. This eliminates variables ΔP_g12, ΔP_g22, ΔP_g53,ΔP_g54, ΔP_g55, ΔP_g63, ΔP_g64 and ΔP_g65, from the optimization problem. The output of this exercise is also given in table 4 - values $P^1{}_{gij}$. These trades are still profitable and, according to the proposed model, they allow the generation owners to maximize their satisfaction.

generator i	load j	$P^o{}_{gij}$ (MW)	$P^1{}_{gij}$ (MW)
1	3	10.00	45.00
1	4	40.00	0.00
1	5	60.00	24.74
2	3	35.00	0.00
2	4	0.00	40.00
2	5	0.00	35.26
5	2	10.00	10.00
6	2	10.00	10.00

Tab. 4 - Trades: initial ($P^o{}_{gij}$) and after validation ($P^1{}_{gij}$).

6. CONCLUSIONS

In this paper the restructuring process of electric industry was addressed. In this scope several problems and challenges were identified, namely the need to integrate several types of uncertainties in models, and the need for a technical validation step if the electricity market is organized in terms of multilateral trades. For both of these two topics models integrating information characterized by fuzzy sets were presented. For the first one, a planning methodology integrating both probabilistic and fuzzy data is described. As a result we obtain useful information regarding the most adequate reinforcement strategies that reduce the risk felt by the system. This is an innovative approach in which two different types of uncertainties are involved in a complementary way. For the second one, one presents an optimization formulation to maximize the level of satisfaction felt by generation entities in a multilateral trade environment guarantying that trades remain profitable. Models like those will most likely be an important aid in the future to ensure that power systems are safely operated.

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