A SIMULATED ANNEALING APPROACH TO DEAL WITH CONGESTION PROBLEMS IN TRANSMISSION NETWOKS

Mário Helder Gomes
Departamento de Engenharia Electrotécnica da Escola Superior de Tecnologia de Tomar – Instituto Politécnico de Tomar
Quinta do Contador, Estrada da Serra
2300 Tomar – Portugal
mgomes@ipt.pt

João Tomé Saraiva
FEUP/DEEC – Faculdade de Engenharia da Universidade do Porto
INESC Porto – Instituto de Engenharia de Sistemas e Computadores do Porto
Praça da Republica, 93, 4050-497 Porto – Portugal
jsaraiva@fe.up.pt

Abstract – In this paper we present four models of increasing complexity and completeness to evaluate the technical feasibility of a set of contracted powers according to commercial agreements established between generation entities and retailers, distribution companies or eligible consumers. In order to solve these optimization problems we used Simulated Annealing, SA, due to its capacity in escaping from local optima and its implementation easiness. The developed approach is illustrated using a Case Study based on the IEEE 24 bus system.

1. INTRODUCTION

The development of new organizational structures [1] in the electric sector lead to several problems and challenges that have to be solved in a transparent and accountable way. Due to the horizontal and vertical reorganization of the sector, a large number of new agents emerged as:

- generation, retailing entities and eligible consumers;
- network service companies – both at the transport and distribution levels;
- ancillary service providers;
- regulatory boards and coordinating entities as System and Market Operators.

In terms of the transport, the grid is now considered the physical location where the market is established but, due to the Kirchoff Laws, the schedules comunicated to the System Operator either from Centralized Pool Markets or due to Bilateral Contracts can be unfeasible from a technical point of view. In this sense, network congestion clearly corresponds to one of the major concerns in today systems since it creates bottlenecks that prevent the implementation of purely market driven schedules. Therefore, although congestion is addressed in several ways in different countries and markets, it is our belief that research must continue on this topic to conceive and develop new methodologies [2, 3, 4, 5].

In this paper we present a set of models to deal with network congestion. These models aim at analyzing schedules from a purely technical point of view leading to a decision whether a set of bilateral contracts and pool economic dispatches are technically feasible or not. If not, the models aim at identifying changes on those schedules according to different criteria. These models have different nature and will be described in ascending order of complexity naturally allowing the comparison of their results at a final section of the paper. The first model aims at identifying those changes considering that the objective is to minimize the square of the sum of the deviations between initially scheduled and final approved injections. The remaining three models aim at maximizing the overall degree of satisfaction felt by different entities in the market. The satisfaction level is defined using concepts from Fuzzy Set Theory. Apart from this classification, the four models can also be grouped according to their DC or AC nature. In this sense, Models 1 and 2 correspond to merely DC approaches while Models 3 and 4 integrate the full AC power flow equations thus leading to more realistic results. Finally, using the ideas behind Model 3, it should be emphasized that Model 4 admits injections both from Pool centralized markets and from bilateral contracts. This corresponds to the current international trend in terms of implementing market mechanisms in the electricity sector since most of today's implementations correspond to hybrid versions in which coexist pool and bilateral contract approaches.

The paper results from the Master Thesis of the first author [6] and it is organized as follows. After this introductory section, the four referred Technical Validation Models are described in Section 2. Section 3 describes the solution algorithm corresponding to the Simulated Annealing meta-heuristic. Section 4 presents results obtained with a Case Study based on the IEEE 24 bus system as well as comparisons between results from different models and in Section 5 the most relevant conclusions will be drawn.

2. TECHNICAL VALIDATION MODELS

2.1. Model 1 – Minimization of deviations

The first technical validation model adopts the DC model to evaluate the technical operating conditions of the network and it aims at identifying a new set of contracted powers between generation entities and retailing or distributions ones that differ from the initially agreed as little as possible. This model is formulated by (1) to (7) and the objective function to be minimized corresponds to the sum of the squares of the deviations between initially contracted and final technically validated powers.

$$\min \quad z = \sum (\Delta Pg_{ij})^2 \tag{1}$$

$$\text{subj.:} \; \sum (Pg_{ij}^0 + \Delta Pg_{ij}) = PL_j \tag{2}$$

$$Pg_i^{min} \le \sum (Pg_{ij}^0 + \Delta Pg_{ij}) \le Pg_i^{max} \tag{3}$$

$$-P_k^{max} \le \sum a_{ki} (\sum Pg_{ij}^0 - PL_i + \sum \Delta Pg_{ij}) \le P_k^{max} \tag{4}$$

$$0 \le Pg_{ij}^0 + \Delta Pg_{ij} \le PL_j \tag{5}$$

$$\sum Cc(Pg_{ij}^0 + \Delta Pg_{ij}) - Cg(\sum Pg_{ij}^0 + \sum \Delta Pg_{ij}) \ge 0{,}0 \tag{6}$$

$$\Delta Pg_{ij} \in \Re \tag{7}$$

In this formulation, Pg_{ij}^0 represents the initial contracted power between generator i and load j, ΔPg_{ij} represents the changes on Pg_{ij}^0 as a result of the technical validation study, PL_j represents the active load connected to node j, Pg_i^{min} and Pg_i^{max} are the minimum and maximum generations of generator i, a_{ki} represents the sensibility coefficient translating the influence of the injected power in node i in the active flow in branch k and P_k^{max} represents the maximum value of the active power flow in branch k.

As referred before, this formulation aims at resizing generation/demand contracted powers, if that is strictly necessary from a technical point of view. The minimization of the sum the squares of contracted powers is subjected to a number of constraints:

- constraints (2) ensure that each load j is supplied by a set of contracted powers.;
- constraints (3) and (4) impose the min and max limits on active generations and on active branch flows;
- constraints (5) impose the admissible ranges of variation to the contracted power between each generator i and each load j;
- constraints (6) enforce that the modified contracted powers still lead to profits.

The profit of generator i is given by the difference between:

- the sum of the amounts paid by load j that has a contract with generator i. The amount each load agreed to pay is expressed by the function Cc;
- the generation cost function of generator i represented by Cg.

2.2. Model 2 – Maximization of the satisfaction degree using the DC model

In the previous model, the expected initial profits of generators can vary in a substantial way when comparing the initially expected values with the ones related with technically approved contracted powers. This situation should be minimized as most as possible because it represents a change in the expectations of the agents eventually imposed by congestion management. Since changes in contracted powers have a direct impact on the flow of money, the technical validation study should be conducted in a transparent and accountable way, in the sense that large reductions of profits on a particular agent together with large increases on others should be carefully considered.

To prevent large variations of these profits, Model 2 aims at computing positive or negative deviations ΔPg_{ij} to be imposed on the initial contracted values Pg_{ij}^0 so that the profits related to each generation entity are decreased as little as possible. In this scope, it is built a Fuzzy Membership Function – FMF - for each generator that expresses the degree of satisfaction felt by each generating entity regarding a given level of profits [7]. To build this FMF we considered the profit each generator expects to obtain if the initially contracted powers are approved, Prf_i^0. Let us also consider that each generator i specifies a tolerance ε that it admits to affect its profit Prf_i^0. This allows us to build the FMF depicted in Figure 1.

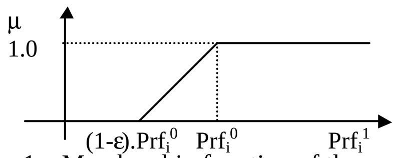

Figure 1 – Membership function of the profit of generator i.

According to this Figure profits lower than $(1-\varepsilon).Prf_i^0$ are not desired given their membership degree is 0.0. Profits in $[(1-\varepsilon).Prf_i^0; Prf_i^0]$ are accepted with increasing values of their membership degree, from 0.0 to 1.0. Finally, profits larger than Prf_i^0 are completely satisfactory so that their membership degree is 1.0.

Using these ideas, the technical validation study corresponds now to the formulation (8) to (15) admitting once again that the DC model is used to represent the operation of the power system.

$$\max \quad z = \mu \tag{8}$$

$$\text{subj.:} \; \sum (Pg_{ij}^0 + \Delta Pg_{ij}) = PL_j \tag{9}$$

$$Pg_i^{min} \le \sum (Pg_{ij}^0 + \Delta Pg_{ij}) \le Pg_i^{max} \tag{10}$$

$$-P_k^{max} \le \sum a_{ki} (\sum Pg_{ij}^0 - PL_i + \sum \Delta Pg_{ij}) \le P_k^{max} \tag{11}$$

$$0 \le Pg_{ij}^0 + \Delta Pg_{ij} \le PL_j \tag{12}$$

$$Prf_i^1 \ge (1-\varepsilon) Prf_i^0 + \mu \, \varepsilon \, Prf_i^0 \tag{13}$$

$$0{,}0 \le \mu \le 1{,}0 \quad (14)$$

$$\Delta Pg_{ij} \in \Re \quad (15)$$

In this formulation PL_j, Pg_i^{min} and Pg_i^{max}, a_{ki} and P_k^{max} have the meaning already indicated for Model 1. Constraints (9), (10), (11) and (12) are similar to constraints (2), (3), (4) and (5) of Model 1. Therefore, Model 2 is similar to Model 1 except in what regards the objective function and constraints (13).

Regarding the objective function we are now maximizing the membership degree μ interpreted as the satisfaction degree felt by generators participating in the market. When maximizing this degree we are in fact indicating that initially contracted powers can be changed but those changes should be selected so that the satisfaction degree remains as high as possible.

Constraints (13) are included to assure that the profit of generator i is not reduced more than the value determined by the tolerance already specified. These constraints are essentially different from the ones in Model 1. In Model 1, constraints (6) correspond in fact to impose 0.0 as the minimum limit on the profit of each generator. This means that the results could display large variations in the profits, some ones being largely reduced while other ones being eventually very much increased. Model 2 deals with this problem by considering a tolerance ε on the profit change and by maximizing the membership degree of the profit.

2.3. Model 3 – Maximization of the satisfaction degree using the AC model

Model 3 corresponds to an upgraded version of Model 2 in the sense that it replaces the DC based model by a full AC version. The model is now represented by the formulation (16) to (28).

$$\max \quad z = \mu \quad (16)$$

$$\text{subj} \quad Pg_k - PL_k = f_1(V,\theta) \quad (17)$$

$$Qg_k - QL_k = f_2(V,\theta) \quad (18)$$

$$-P_k^{max} \le f_3(V,\theta) \le P_k^{max} \quad (19)$$

$$V_k^{min} \le V_k \le V_k^{max} \quad (20)$$

$$Pg_i^{min} \le Pg_i^1 \le Pg_i^{max} \quad (21)$$

$$Pg_i^1 = \sum (Pg_{ij}^o + \Delta Pg_{ij}) + Ploss_i \quad (22)$$

$$\sum Ploss_i = \sum f_4(V,\theta) \quad (23)$$

$$\sum (Pg_{ij}^o + \Delta Pg_{ij}) = PL_j \quad (24)$$

$$0{,}0 \le Pg_{ij}^o + \Delta Pg_{ij} \le PL_j \quad (25)$$

$$Prf_i^1 \ge (1-\varepsilon)\, Prf_i^o + \mu\, \varepsilon\, Prf_i^o \quad (26)$$

$$0{,}0 \le \mu \le 1{,}0 \quad (27)$$

$$\Delta Pg_{ij} \in \Re \quad (28)$$

In this formulation f_1 and f_2 represent the active and reactive power flow equations for node k, f_3 represents the active power flow expression for branch k and f_4 is the active power loss expression for a given branch in terms of voltage magnitudes and phases in its extreme buses. According to this notation, constraints (19), (20) and (21) impose minimum and maximum values to branch flows, to voltage magnitudes and to active generations. Constraints (22) express the generation of generator connected to node i as a function of the initially contracted powers, of the output deviations and of $Ploss_i$. This output variable represents the amount of power each generator will be scheduled to contribute to balance active losses in the grid. Constraint (23) impose that the global value of branch active losses are balanced against the contributions scheduled to each generator. Finally, constraints (24) to (28) are similar to constraints already included in Model 2.

2.4. Model 4 – Maximization of the satisfaction degree using the AC model and pool and bilateral contract injections

Models 1, 2 and 3 consider that the relationship between generation and demand (either represented by retailers, distribution companies or eligible consumers) is exclusively performed by Bilateral Contracts. Model 4 enhances Model 3 so that one can consider in the technical validation study both information from bilateral contracts and schedules from centralized Pool markets. In this sense, it becomes a more realistic formulation given that current market structures in most of the countries correspond to mixed Pool/Bilateral Contract approaches. Model 4 is represented by the formulation (29) to (44).

$$\max \quad z = \mu \quad (29)$$

$$\text{subj} \quad Pgc_k^1 + Pgp_k^1 - PLc_k - PLp_k = f_{1k}(V,\theta) \quad (30)$$

$$Qg_k - QL_k = f_{2k}(V,\theta) \quad (31)$$

$$-P_k^{max} \le f_{3k}(V,\theta) \le P_k^{max} \quad (32)$$

$$V_k^{min} \le V_k \le V_k^{max} \quad (33)$$

$$Pgp_i^{min} \le Pgp_i^1 \le Pgp_i^{max} \quad (34)$$

$$Pgc_i^{min} \le Pgc_i^1 \le Pgc_i^{max} \quad (35)$$

$$Pgc_i^1 = \sum_j (Pgc_{ij}^0 + \Delta Pgc_{ij}) + Ploss_i \quad (36)$$

$$Pgp_i^1 + Pgp_i^0 + \Delta Pgp_i + Ploss_i \quad (37)$$

$$\sum_{\text{all c and p gen}} Ploss_i = \sum_k f_{4k}(V,\theta) \quad (38)$$

$$\sum_i (Pgc_{ij}^0 + \Delta Pgc_{ij}) = PLc_j \quad (39)$$

$$0 \le Pgc_{ij}^0 + \Delta Pgc_{ij} \le PLc_j \quad (40)$$

$$\sum_i (Pgp_i^0 + \Delta Pgp_i) = \sum_j PLp_j \quad (41)$$

$$Prf_i^1 \ge (1-\varepsilon).Prf_i^0 + \mu.\varepsilon.Prf_i^0 \quad (42)$$

$$0.0 \le \mu \le 1.0 \quad (43)$$

$$\Delta Pg_{ij} \in \Re \quad (44)$$

In this formulation, the generation schedules related to the Pool centralized market are denoted with p while the ones related to bilateral contracts include c. It should be noticed that constraints (36), (37) and (38) indicate that all p and c generators contribute to balance active losses and that all p and c generators can potentially see they initially scheduled powers changed as a result of the technical validation study.

3. SOLUTION ALGORITHM

3.1. Generics about Simulated Annealing

The four previous problems correspond to non-linear optimization problems that could be addressed by any non-linear optimization method. However, we adopted a Simulated Annealing approach [8] given that this meta-heuristic is remarkably easy to be implemented and it is reported to output good results in terms of identifying good solutions for several types of problems. One of the basics features of Simulated Annealing – together with other meta-heuristics as, for instance, Genetic Algorithms – is its ability to escape from local optima. This feature is obtained admitting transitory relaxation of the optimality condition. This means that the algorithm admits intermediate moves to solutions worse than the current one. This is admitted in order to widen the area of the solution space under inspection and, therefore, to turn it possible to select a more adequate and promising area for a more detailed and closer analysis.

Simulated Annealing has a clear analogy with thermodynamic problems in the sense that the solutions or alternatives of a combinatorial problem are equivalent to states of thermodynamic systems, the evaluation function is related to the energy of each state and the control parameter used to accept new solutions is related to the temperature of thermodynamic systems. The algorithm represents a cooling process performed in a sufficiently slow pace so that the parts of a system have time to organize themselves in order to get a minimum energy stadium. Admitting that a generic function f is to be minimized the basic algorithm works like this:

i) Initialization – select an initial solution x_1 in the space of solutions X;
Assign $f(x_1) \rightarrow f^*$ and $x_1 \rightarrow x^*$;

ii) Step n=1,2,…; x_n denotes the current solution;
- obtain x at random in the neighborhood of x_n;
- if $f(x) \leq f(x_n)$ then $x \rightarrow x_{n+1}$;
  - if $f(x) \leq f^*$ then $f(x) \rightarrow f^*, x \rightarrow x^*$
- else, get a random number p in $[0,1]$
  - if $p < p(n)$ then $x \rightarrow x_{n+1}$;

iii) End if stopping condition is reached. Otherwise return to ii).

In this algorithm, x* and f* denote the current optimal solution and p is the probability determining the acceptation of worse solutions. Finally, p(n) is the acceptance probability of solution x_n typically given by (45).

$$p(n) = e^{-\frac{\Delta fn}{K.T(n)}} \qquad (45)$$

In this expression, K represents a cooling constant, Δfn is the change of the evaluation function from iteration n-1 to iteration n and T(n) is the temperature of the cooling process at iteration n. This temperature is also higher in the beginning and gets reduced as the process goes on. This means that worse solutions are more likely to be accepted in the beginning so that the search covers a wider area of the solution space. As the search proceeds, p(n) is reduced so that the search gets concentrated in a selected area.

3.2. Implemented approach

Considering the four formulations corresponding to Models 1 to 4, the adoption of Simulated Annealing lead to the algorithm represented in Figure 2. In this algorithm w is the counter of worse solutions, n is the counter of the number of iterations and T is the Temperature parameter. In this Figure * designates < in case of a minimization problem (as in Model 1) and > in case of maximization one (as in Models 2, 3 and 4).

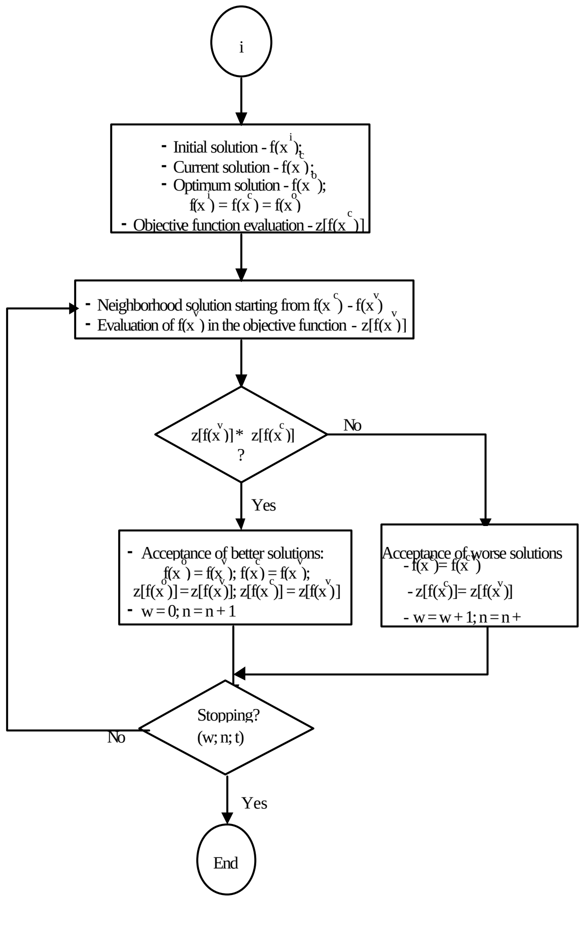

Figure 2 – Algorithm of the Simulated Annealing Implementation.

The evaluation function f included in Figure 2 corresponds to the objective function z of each Model plus:

- a sum of penalty terms activated in case any constraint of each Model is violated;
- a sum of penalty terms activated if Power Not Supplied variables are non-zero.

As an example expression (46) corresponds to the evaluation function used for Model 1 while (47) was used for Model 2. In these expressions g represent the penalty coefficients used to enforce violated constraints and to penalize power not supplied.

$$f(x) = (\Delta Pg_{ij})^2 + \sum (g_{constr,Model1}.Constr_{k,Model1}) + \\ + g_{PNS}.PNS \tag{46}$$

$$f(x) = \mu - \sum (g_{constr,Model2}.Constr_{k,Model2}) + \\ - g_{PNS}.PNS \tag{47}$$

4. CASE STUDY

4.1. System data

The previous formulations and the solution algorithm were tested using a Case Study based on the IEEE 24 bus/38 branch test system presented in Figure 3. Regarding the data of this network, the original load values and maximum generations (as can be obtained from [9] were multiplied by 1.8 and by 2.0.

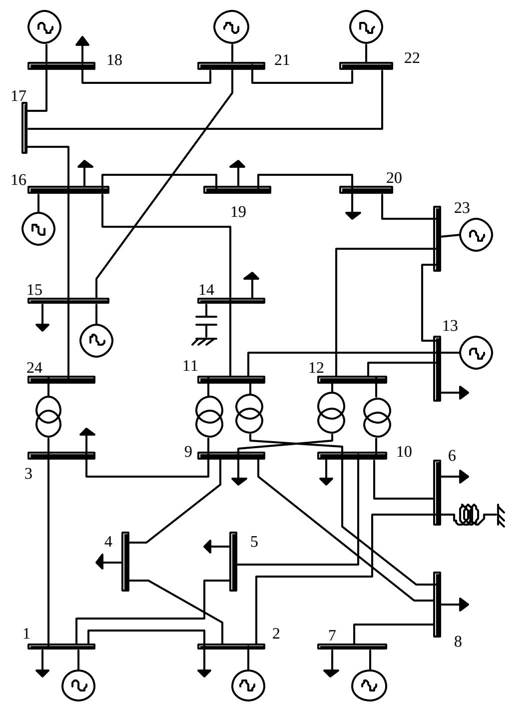

Figure 3 – IEEE 24 bus test system.

The generator cost functions and the load remuneration functions were specified according to expressions (48) and (49). For these functions, Table I indicates the values used for coefficients a and b in case of generation functions and c in case of load functions.

$$C_g(P_g) = a.P_g + b.P_g^2 \quad \$/h \tag{48}$$

$$C_l(P_l) = c.PL \quad \$/h \tag{49}$$

Table I – Data for generator cost and load remuneration functions.

Bus	a	b	c
1	4.00	0.003	13.00
2	3.50	0.004	12.50
3	-	-	11.00
4	-	-	15.00
5	-	-	15.50
6	-	-	13.50
7	5.00	0.002	13.00
8	-	-	13.00
9	-	-	12.50
10	-	-	11.80
13	6.00	0.003	10.60
14	-	-	11.00
15	2.50	0.004	10.50
16	5.50	0.003	16.00
18	9.00	0.001	12.00
19	-	-	13.40
20	-	-	13.60
21	8.00	0.001	-
22	2.00	0.004	-
23	5.75	0.003	-

4.2. Results obtained with Model 1

In the first place we used Model 1 to analyze the technical feasibility of a set of contracts. Table II indicates in its second column the initial generation powers as the sum of the established contracts. For these powers there is congestion in branch 7-8 since the power flow in this branch – computed according the DC model - is 310 MW and the capacity of that branch is 175 MW. The outputs of Model 1 are indicated in columns 3 and 4 of Table II. Column 3 includes the changes in the contracted powers and column 4 indicates the final approved powers. The 135 MW of excessive flow from node 7 to 8 is reallocated to other generators so that, according to Model 1, the sum of the squares of the deviations is minimized.

Table II – Initially contracted powers, deviations and final powers.

Gen i	Initial powers (MW)	Deviations (MW)	Final powers (MW)
1	370.00	13.00	383.00
2	366.00	19.00	385.00
7	535.00	-135.00	400.00
13	1052.00	12.00	1064.00
15	395.00	14.00	409.00
16	280.00	15.00	295.00
18	530.00	16.00	546.00
21	550.00	12.00	562.00
22	330.00	16.00	346.00
23	850.00	18.00	868.00

4.3. Results obtained with Model 2

In a second simulation we used Model 2 to perform the technical validation study. In this case, we specified 20% for the value of the tolerance parameter ε. The results obtained with this Model are presented in Table III. As in the previous case, column 2 indicates the initially contracted generations, column 3 includes the deviations and column 4 the final generations as outputs of the Simulated Annealing procedure.

Table III - Initially contracted generations, deviations and final generations.

Gen i	Initial powers (MW)	Deviations (MW)	Final powers (MW)
1	370,00	15,00	385,00
2	366,00	19,00	385,00
7	535,00	-135,00	400,00
13	1052,00	-43,00	1009,00
15	395,00	6,00	401,00
16	280,00	16,00	296,00
18	530,00	82,00	612,00
21	550,00	15,00	565,00
22	330,00	22,00	352,00
23	850,00	3,00	853,00

4.4. Results obtained with Model 3

Finally, we used the AC based Model 3 to perform the technical validation study. The results are indicated in Table 4. Apart from the initial contracted generations, deviations and final contracted generations in columns 2, 3 and 4, this Table also includes the contribution of each generator to compensate transmission losses, in column 5, and the total generation of each machine as a sum of the contracted values plus the loss allocated amount, in column 6.

Table IV- Initially contracted powers, deviations, contracted powers, active losses allocated to each generator and total generations.

Gen i	Initial powers (MW)	Deviations (MW)	Contracted powers (MW)	Losses (MW)	Total powers (MW)
1	370,00	-39,00	331,00	5,12	336,12
2	366,00	-13,00	353,00	7,58	360,58
7	535,00	-135,00	400,00	0,00	400,00
13	1052,00	2,00	1054,00	41,80	1095,80
15	395,00	-9,00	386,00	22,10	408,10
16	280,00	12,00	292,00	13,53	305,53
18	530,00	27,84	557,84	0,80	558,64
21	550,00	13,08	563,08	3,31	566,39
22	330,00	-27,92	302,08	6,14	308,22
23	850,00	169,00	1019,00	4,00	1023,00

4.4. Comments

The results coming from these 3 Models have an important conceptual difference, namely when going from Model 1 to Models 2 and 3. Model 1 is concerned with the identification of a feasible set of contracts disregarding the potentially large variations in generation profits. These variations between expected and real profits are display in columns 2 and 4 of Table V. One can notice that generator 7 faces a reduction of 22,5% in its expected profits while other generator experience increases of 2 to 4% in their profits.

Regarding Models 2 and 3, Table V displays the minimum allowable profit (column 3) determined by the 20% value specified for ε as well as the final profits for each of the models and the respective degree of satisfaction (columns 5 and 6 for Model 2 and 7 and 8 for Model 3). In the case of Model 2, generator 7 experiences a reduction of 17,2% in its profit. In Model 3 the largest reduction also occurs for generator 7 and it corresponds to 13,9%.

Table V – Profits of the generators obtained with Models 1, 2 and 3 (initial profit, minimum profit admitted for generator i, final profit of the generator i, and satisfaction degree felt by generator i).

			Model 1	Model 2		Model 3	
Gen i	Prf_i^o ($/h)	min Prf_i ($/h)	Prf_i ($/h)	Prf_i ($/h)	μ_i	Prf_i ($/h)	μ_i
1	2881.80	2305.44	2955.43	2946.82	1.0	2713.21	0.71
2	2987.47	2389.98	3096.60	2995.50	1.0	2803.26	0.69
7	3307.55	2646.04	2564.00	2739.00	0.14	2874.36	0.35
13	3749.08	2999.27	3754.61	3761.55	1.0	3570.45	0.76
15	2673.40	2138.72	2772.37	2802.89	1.0	2751.31	1.0
16	1704.80	1363.84	1777.42	1707.55	1.0	1543.32	0.53
18	1891.10	1512.88	1929.48	1895.85	1.0	1823.21	0.82
21	1222.50	978.00	1261.15	1309.67	1.0	1429.58	1.0
22	3072.40	2457.92	3202.13	3224.48	1.0	2782.31	0.53
23	3115.00	2492.00	3135.72	3200.82	1.0	3308.86	1.0

5. CONCLUSIONS

The implementation of market mechanisms raised a number of challenges namely in terms the re-organization of the industry in a more decentralized way while maintaining high levels of security. This process lead to the pool model and to the bilateral contract approach as ways to establish relations between the generation and the demand sides of the system. However, the operation of power systems mustn't be based in a purely economic basis since behind the market driven procedures there are the networks and the need to comply with Kirchoff Laws. In this sense, congestion problems must be dealt with in a transparent, technical and accountable way. In an attempt to contribute to deal with this problem we described four models of increasing complexity that retain a clear connection with traditional OPF problems system operators are familiar with. Therefore, it is our belief that this kind of procedures, while addressing congestion problems in a realistic way, have the potential to be applied in control centers requiring little adaptation regarding traditional modules.

References

[1] W. Hogan, "Competitive Electricity Market Design: A Wholesale Primer", Center for Business and Government, Harvard University, Massachusetts, December 1998, available in http://faculty-gsb.stanford.edu/wilson/E542.

[2] F. F. Wu, "Coordinated Multilateral Trades for Electric Power Networks", Proceedings of 12th PSCC Conference, Dresden, August 1996.

[3] J. Finney, H. Othman, W. Rutz, "Evaluating Transmission Congestion Constraints in System Planning", IEEE Trans. on Power Systems, vol. 12, no. 3, August 1997.

[4] J. W. M. Cheng, F. D. Galiana, D. T. McGillis, "Studies of Bilateral Contracts with Respect to Steady State Security in a Deregulated Environment", Proceedings of PICA'97, Columbus, Ohio, May 1997.

[5] J. Tomé Saraiva, "An Approach to Enhance Power System Security in Market Environment With Third Party Access", EPSOM'98, Zurich, September 1998.

[6] M. Helder Gomes, "Models to Validate Contracts from a Technical Point of View in Competitive Environment" (in Portuguese), Master Thesis, FEUP, Porto, Portugal, Dec. 2000.

[7] H. J. Zimmermann, "Fuzzy Set Theory and Its Applications", Kluwer Nijhoff, Boston, 1985.

[8] E. Arts, J. Korst, Simulated Annealing and Boltzmann Machines, John Wiley & Sons, New York, 1990.

[9] IEEE Reliability Test System Task Force, "IEEE Reliability Test System", IEEE Trans. on PAS, vol. 98, no. 6, Nov./Dec. 1979.