An Approach to Enhance Power System Security in Market Environment with Third Party Access

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Abstract: In recent years the electric industry started to be restructured in a process placing several challenges. One of the new possibilities corresponds to establish contracts between generation providers and distribution companies or eligible consumers. However, these contracts shall be investigated to check if violations of security or technical constraints occur. In this paper, we present DC and AC models to investigate and eventually change these contracts so that the overall satisfaction degree felt by the participants in the market is maximized ensuring that those constraints are not violated. At the end of the paper we present a case study to illustrate the application of these models.

Keywords: Bilateral Contracts, Congestion, Satisfaction Degree, Fuzzy Sets.

1 Introduction

Till the end of the eightieth almost all power systems were organized in vertically integrated utilities covering, in some cases, all the area of a country. In other cases, several utilities operated in the same country but there were franchised territories so that, for each consumer, there was always one only supplier in a natural monopoly basis. The Chilean movement towards a change [1], still in the seventieth, rapidly spread to other counties in the eightieth and in the ninetieth. The change in England and Wales, in USA, and more recently the common electricity market of Sweden and Norway and the Finnish and Spanish processes are examples of these moves. Most of the discussions in Europe are taking place given that several countries are EU members. In this scope, the EU Commission already issued a Directive considered as a first attempt to organize an internal EU electricity market.

The access to transmission networks is crucial if transparency and non-discriminatory treatment are to be given to all participants in the market [2]. The discussion on these issues led to two basic models: the Pool model [3] similar to the one existing in England and Wales and the Bilateral Contract one [4]. Among the applications needed to aid the operation of power systems, the analysis and validation of contracts from a technical point of view is certainly an important one. In this scope one admits that there is a direct commercial relationship between generation providers and distributors or eligible consumers. However, one easily recognizes that a set of non-coordinated contracts can lead to the violation of security or technical constraints of the system. This is why those contracts should be investigated from a technical point of view and changes should be suggested only if they are necessary to meet system constraints. In [5] it is presented a model for the Bilateral Contracts approach using a Transactions Matrix and adopting a Linear Programming formulation that includes constraints related to the generator and branch limits. This formulation can be used, for instance, to maximize individual contracts or combinations of bilateral contracts.

In this paper, we firstly present a simplified version of the validation problem including the DC model and aiming at minimizing the sum of the squares of the deviations of the contracted powers needed to enforce a set of constraints. Afterwards, we present a complete AC version now aiming at maximizing the satisfaction degree felt by generation owners given that a membership function of the profits is built using concepts from the Theory of Fuzzy Sets. This model outputs active generation values, reactive generations, voltages and phases, and the contribution of each generator to balance active losses. In section 3, we present results obtained with a case study to illustrate the application of those models.

2 Technical Validation Models

2.1 Characterization of the Problem

Let us consider that generator entities contract selling electricity to distribution companies or eligible consumers. These contracts shall be profitable meaning that the remuneration paid by all clients to a generator owner has to be larger than its generation cost. Let Cg_i, Cl_j and Pg_{ij} be the cost function of generator i ($/MWh), the value load j admits to pay ($/MWh) and the active power contracted by generator i with load j (MW). These contracts shall be profitable, that is the profit of generator i, Prf_i, must check condition (1). These contracted values will now be submitted to a technical validation study that leads to changes in the contracted values only if they are necessary to enforce system constraints. Let us assume that Pg^o_{ij}, ΔPg_{ij} and Pg^1_{ij} are the initially contracted powers, the deviations imposed by the validation study and the final contracted powers. These final values must still lead to a set of profitable trades (2).

$$Prf_i = \sum_j Cl_j(Pg_{ij}) - Cg_i(\sum_j Pg_{ij}) \geq 0.0 \qquad (1)$$

$$Prf^1_i = \sum_j Cl_j(Pg^o_{ij} + \Delta Pg_{ij}) - Cg_i(\sum_j (Pg^o_{ij} + \Delta Pg_{ij})) \geq 0.0 \qquad (2)$$

2.2 Minimization of Deviations

In this model one aims at identifying a new set of contracted powers such that the sum of the squares of the differences between their final and initial values is minimized. The formulation (3) to (9) adopts the DC power flow model to describe the operation of the network.

$$\min \quad z = \sum \sum (\Delta Pg_{ij})^2 \qquad (3)$$

$$\text{subj.} \quad \sum (Pg^o_{ij} + \Delta Pg_{ij}) = Pl_j \qquad \text{(for each load j)} \qquad (4)$$

$$Pg^{min}_i \leq \sum (Pg^o_{ij} + \Delta Pg_{ij}) \leq Pg^{max}_i \qquad \text{(for each gen. i)} \qquad (5)$$

$$-P^{max}_k \leq \sum a_{ki}.(\sum Pg^o_{ij} + \sum \Delta Pg_{ij} - Pl_i) \leq P^{max}_k \qquad \text{(for each branch k)} \qquad (6)$$

$$0 \leq Pg^o_{ij} + \Delta Pg_{ij} \leq Pl_j \qquad \text{(for each i and each j)} \qquad (7)$$

$$\sum Cl(Pg^o_{ij} + \Delta Pg_{ij}) - Cg(\sum Pg^o_{ij} + \sum \Delta Pg_{ij}) \geq 0.0 \qquad \text{(for each gen. i)} \qquad (8)$$

$$\Delta Pg_{ij} \in \Re \qquad (9)$$

In this model, Pl_j is node j active load, Pg^{min}_i and Pg^{max}_i are the limits of generator i, a_{ki} is the sensibility coefficient of branch k flow regarding the injected power in node i and P^{max}_k is the maximum flow in branch k. Constraints (4) are a decoupled version of the load/generation balance equation and are included to ensure that each load j is feed by a set of contracted powers. Constraints (5) and (6) impose min and max bounds to the generated powers and to the branch flows. Constraints (7) define the range of the power that can be contracted between each generator and each load while (8) impose that the new trades remain profitable.

2.3 Maximization of the Satisfaction Degree

Constraints (8) of the previous model ensure that the final contracts are profitable. However, this does not avoid that some profits are reduced while others are increased. This effect can be prevented ensuring that all generation entities remain satisfied with the final values of profits. The satisfaction level can be modelled by a membership function in the scope of the Theory of Fuzzy Sets [6], such as the one sketched in figure 1. $\Pr f_i^o$ is the profit of generator i computed with the initial contracts. Profits larger than $\Pr f_i^o$ are fully satisfactory while profits smaller than $(1-\varepsilon).\Pr f_i^o$ are assigned a 0.0 degree where ε is a value in [0.0;1.0] representing the maximum reduction that generator owners admit to affect their profits.

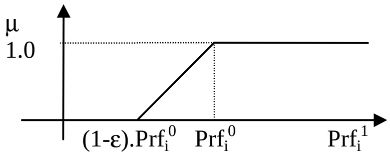

Figure 1 - Membership function of the profit of generator i.

The technical validation problem aims at identifying a set of new contracted powers that maximize the overall satisfaction degree, μ, while not violating security and technical constraints of the system. To get a more realistic picture of the operation of the network, the validation problem is formulated by (10) to (22) using the AC power flow equations.

$$\max \quad z = \mu \tag{10}$$
$$\text{subj.} \quad Pg_n - Pl_n = f_{1n}(V,\theta) \quad \text{(for each node n)} \tag{11}$$
$$Qg_n - Ql_n = f_{2n}(V,\theta) \quad \text{(for each node n)} \tag{12}$$
$$-P_k^{max} \le f_{3k}(V,\theta) \le P_k^{max} \quad \text{(for each branch k)} \tag{13}$$
$$V_n^{min} \le V_n \le V_n^{max} \quad \text{(for each node n)} \tag{14}$$
$$Pg_i^{min} \le Pg_i^1 \le Pg_i^{max} \quad \text{(for each gen. i)} \tag{15}$$
$$Pg_i^1 = \sum_j (Pg_{ij}^o + \Delta Pg_{ij}) + Ploss_i \quad \text{(for each gen. i)} \tag{16}$$
$$\sum_i Ploss_i = \sum_k f_{4k}(V,\theta) \tag{17}$$
$$\sum_i (Pg_{ij}^o + \Delta Pg_{ij}) = Pl_j \quad \text{(for each load j)} \tag{18}$$
$$0 \le Pg_{ij}^o + \Delta Pg_{ij} \le Pl_j \quad \text{(for each i and each j)} \tag{19}$$
$$\Pr f_i^1 \ge (1-\varepsilon).\Pr f_i^o + \mu.\varepsilon.\Pr f_i^o \quad \text{(for each gen. i)} \tag{20}$$
$$0.0 \le \mu \le 1.0 \tag{21}$$
$$\Delta Pg_{ij} \in \Re \tag{22}$$

In this formulation:

- constraints (11) and (12) correspond to the AC power flow equations where f_1 and f_2 are the expressions of the injected active and reactive powers;
- constraints (13) to (15) impose bounds on branch active power flows, voltage magnitudes and active generations. f_{3k} is the expression of the active power flow in branch k;
- constraints (16) represent the generated power in each generator in terms of the initially contracted powers and their deviations. In these expressions the term $Ploss_i$ is included to

represent the active power to be generated by generator i as a contribution to balance active losses. These contributions are obtained as a result of the problem;
- the sum of all these $Ploss_i$ contributions will match the total active power losses computed as a sum of the losses in all system branches. This is modelled by (17) where f_{4k} is the expression of active power losses in branch k;
- constraints (20) enforce the profitable nature of trades corresponding to impose a minimum limit to the profits depending on μ and on the specified tolerance, ε.

Due to the non-linearities of generator cost functions and to the integration of the AC power flow model this formulation corresponds to a non-linear programming problem that can be solved using a gradient approach. As results, this problem gives the deviations of the contracted powers that maximize the satisfaction degree μ, as well as reactive generations, the contribution of each generator to compensate active losses and bus voltages and phases.

3 Application Examples

The presented models were used to study a set of contracts specified for the network of figure 2. In Table I we present the minimum and maximum voltage values, loads and generation capacities. Table II includes the characteristics of the branches. Expressions (23 to 26) and (27 to 30) are the generator cost and load remuneration functions.

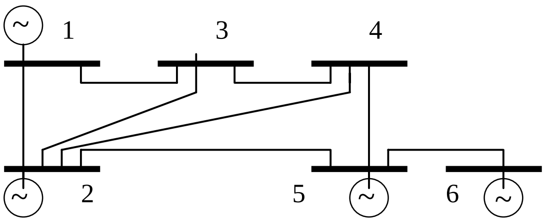

Figure 2 - Network used to illustrate the described models.

Table I - Nodal data.

Node	V^{min} pu	V^{max} pu	Pg^{max} MW	Load MW	Load MVAr
1	0.94	1.06	110.0	---	---
2	0.94	1.06	100.0	20.0	10.0
3	0.94	1.06	---	45.0	30.0
4	0.94	1.06	---	40.0	25.0
5	0.94	1.06	10.0	60.0	40.0
6	0.94	1.06	10.0	---	---

Table II - Characteristics of the branches.

Node i	Node j	r (pu)	x (pu)	P_{ij}^{max}(MW)
1	2	0.02	0.06	55.0
1	3	0.08	0.24	50.0
2	3	0.06	0.18	50.0
2	4	0.06	0.18	50.0
2	5	0.04	0.12	50.0
3	4	0.01	0.03	50.0
4	5	0.08	0.24	50.0
5	6	0.01	0.03	15.0

$$C_g(Pg_1) = 5.Pg_1 + 0.02.Pg_1^2 \quad (23) \qquad C_g(Pg_5) = 3.Pg_5 + 0.025.Pg_5^2 \quad (25)$$

$$C_g(Pg_2) = 4.Pg_2 + 0.03.Pg_2^2 \quad (24) \qquad C_g(Pg_6) = 4.Pg_6 + 0.02.Pg_6^2 \quad (26)$$

$$C_1(Pl_2) = 6.Pl_2 \quad (27)$$

$$C_1(Pl_3) = 12.Pl_3 \quad (28)$$

$$C_1(Pl_4) = 10.Pl_4 \quad (29)$$

$$C_1(Pl_5) = 11.Pl_5 \quad (30)$$

Firstly, the model of section 2.2 was used to validate the contracted Pg_{ij}^o powers of Table III. A DC power flow indicated that the active flow in branch 1-2 - 73.94 MW - violated the limit of 55.0 MW. Therefore, model (3-9) was used to identify the changes on contracted powers. ΔPg_{ij} and Pg_{ij}^1 in Table III are the calculated deviations and the final contracted powers.

Table III - Contracts - initial (Pg_{ij}^o), deviations (ΔPg_{ij}) and final (Pg_{ij}^1) values.

Gen i	Load j	Pg_{ij}^o MW	ΔPg_{ij} MW	Pg_{ij}^1 MW	Gen i	Load j	Pg_{ij}^o MW	ΔPg_{ij} MW	Pg_{ij}^1 MW
1	2	0.00	0.00	0.00	5	2	10.00	-1.87	8.13
1	3	10.00	-7.48	2.52	5	3	0.00	0.62	0.62
1	4	40.00	-7.48	32.52	5	4	0.00	0.62	0.62
1	5	60.00	-7.48	52.52	5	5	0.00	0.62	0.62
2	2	0.00	3.72	3.72	6	2	10.00	-1.87	8.13
2	3	35.00	6.24	41.24	6	3	0.00	0.62	0.62
2	4	0.0	6.24	6.24	6	4	0.00	0.62	0.62
2	5	0.0	6.24	6.24	6	5	0.00	0.62	0.62

In a second step, the AC model of section 2.3 was used to validate the initial contracts considering $P_{12}^{max} = 55.0\,MW$ and $P_{12}^{max} = 40.0\,MW$ and using 30% for ε. The results obtained are presented in Table IV. The satisfaction level is maximum - 1.0 - with $P_{12}^{max} = 55.0\,MW$ and is reduced to 0.8748 with $P_{12}^{max} = 40.0\,MW$. In the second case generations in buses 1, 2, 5 and 6 are 72.13, 83.50, 10.0 and 6.87 MW. Each of these values includes two components: one corresponding to the contracted powers and another one to compensate active losses.

Table IV - Contracts - initial (Pg_{ij}^o), deviations (ΔPg_{ij}) and final (Pg_{ij}^1) values.

			$P_{12}^{max} = 55.0\,MW$		$P_{12}^{max} = 40.0\,MW$	
Gen i	Load j	Pg_{ij}^o MW	ΔPg_{ij} MW	Pg_{ij}^1 MW	ΔPg_{ij} MW	Pg_{ij}^1 MW
1	2	0.00	0.00	0.00	0.00	0.00
1	3	10.00	35.00	45.00	35.00	45.00
1	4	40.00	-40.00	0.00	-40.00	0.00
1	5	60.00	-19.10	40.90	-32.87	27.13
2	2	0.00	0.00	0.00	6.89	6.89
2	3	35.00	-35.00	0.00	-35.00	0.00
2	4	0.00	39.96	39.96	38.38	38.38
2	5	0.00	18.95	18.95	31.97	31.97
5	2	10.00	-0.03	9.97	-2.84	7.16
5	3	0.00	0.00	0.00	0.00	0.00
5	4	0.00	0.00	0.00	1.53	1.53
5	5	0.00	0.02	0.02	0.06	0.06
6	2	10.00	-0.07	9.93	-4.06	5.94
6	3	0.00	0.00	0.00	0.00	0.00
6	4	0.00	0.00	0.00	0.09	0.09
6	5	0.00	0.04	0.04	0.84	0.84

The results obtained with the model presented in section 2.2 show that this is not the most adequate to perform validation studies. Apart from integrating the DC formulation to model system operation, the profitable nature of contracts is only enforced by constraints (8). In this example, these constraints were not enough to prevent increases, in some cases, and decreases, in others, of the profits as one can conclude from analysing the results of table V.

This effect can be avoided if, as in model of section 2.3, we aim at maximizing the satisfaction degree felt by generators. The presented results deserve some comments:

- the model outputs generation values as the sum of the contracted powers and a quantity to compensate active losses. In this example and for $P_{12}^{max} = 40.0\,\mathrm{MW}$, the total active losses are 7.49 MW. From these, 6.24 MW are generated in node 2 and 1.25 MW in 5. The knowledge of such values may contribute to turn more transparent the remuneration of this service, and so, clarify the relations between generators and transmission owners;
- as presented in Table V, an homogeneous reduction of the profits is now obtained despite some generations are increased and others decreased. The crucial fact is that active loads are reallocated to generators so that the final profits are reduced as little as it is necessary;
- this model can still be enhanced by integrating constraints related, for instance, to generation apparent power limits and to line current limits;

Table V - Generation values, profits and variation of profits (%)

			Model 2.2			Model 2.3 for $P_{12}^{max} = 40.0\,\mathrm{MW}$		
Gen i	Pg_{ij}^{o} MW	$Pr\,f_i^{o}$ \$/h	Pg_{ij}^{1} MW	$Pr\,f_i^{1}$ \$/h	%	Pg_{ij}^{1} MW	$Pr\,f_i^{1}$ \$/h	%
1	110.0	388.00	87.56	341.95	-11.87	72.13	375.43	-3.76
2	35.0	243.25	57.44	319.47	+31.33	83,50	234.11	-3.76
5	10.0	27.50	10.00	36.74	+33.60	10.00	26.47	-3.76
6	10.0	18.00	10.00	27.24	+51.24	6.87	17.32	-3.76

4 Conclusions

In this paper we presented models to validate a set of contracted powers in the scope of a bilateral relationship between generation entities and distributors or eligible consumers. This validation process must be conducted in a transparent and non-discriminatory way and only governed by technical issues that can be justified in an objective way. One of the described models aims at maximizing the overall satisfaction level felt by generators and integrates, for accuracy purposes, the AC power flow model. This kind of formulation shows a clear similarity to the well known OPF studies with which Control Center operators are already well acquainted. Therefore, such models can be more easily introduced in Control Centers and can be a valuable aid to maintain the level of security of today power systems.

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