Firm Transmission Rights and Congestion Management in Electricity Markets

Judite Ferreira[1], Zita Vale[1], José Cardoso[2]

[1,2] GECAD – Knowledge Engineering and Decision Support Group
Institute of Engineering – Polytechnic of Porto
Porto, Portugal

[3] CETAV – Centre for Technological, Environmental and Life Studies
University of Trás-os-Montes and Alto Douro, Engineering Department

Abstract – In electricity markets, congestion issues and the right of the access to the grid are very important, because these factors can condition agent participation in the market.
Electricity markets involve a Spot Market resulting in transactions that must be technically managed by a central system operator, namely in what concerns real-time dispatch of generation and transmission resources.
The use of the grid implies the payment of tariffs that require the consideration of several factors to be defined. Agents can buy transmission rights and congestion situations must be considered in these tariffs.
This paper presents a software tool that calculates Firm Transmission Rights, detects and solves congestion problems and calculates the Locational Marginal Prices. As a final result, this tool calculates how much each agent has to pay for grid use.
The paper includes a study case using a nine-bus test network and the analysis of the obtained results.

Keywords: Firm transmission Rights, Locational Marginal Price, OPF, Spot Market

1 Introduction

Transmission congestion management has always been a very important issue in power systems. Presently, congestion management is essential in competitive power markets, because a non efficient congestion management can to put in danger not only the physical system but also the market operation [1].
In this context, market participants can buy a right to transfer power over a constrained transmission path for a fixed price, which is called a Firm Transmission Right (FTR). Transmission rights are so fundamental to an efficient design of competitive electricity markets that their definition must be included in market rules and should not be designed by private commercial entities afterward. However, the specification of transmissions rights is complicated by externalities due to loop flows.
Markets for transmission rights are essentially forward markets for price differentials between various locations on the electrical grid [2-4].
A FTR is a right that has the attributes of both financial and physical transmission rights. FTRs will entitle their owners to share in the distribution of usage charge revenues received by the Independent System Operator (ISO), in the Day-Ahead and Hour-Ahead Markets, in connection with Inter-Zonal Congestion during the period for which the FTR is issued. FTRs will also entitle the registered FTR holder to certain priorities (in the Day-Ahead Market) for the transmission of energy across a congested Inter-Zonal interface [3-8].
In this paper, we present a methodology to be used by the ISO to determine the load FTRs and to compute how much the agents pay to the system and its software implementation [9-12].
This study considers initial contracts between GenCos and Users that correspond to the bilateral contracts for a year [5], [12].
It is necessary to verify if there are congestion situations. If this happens, a new dispatch (re-dispatch) must be deployed and the congestion costs must be evaluated and distributed by the Loads. After this, it is necessary to calculate the FTR congestion credit, the FTR congestion charges, the energy sales, and the energy purchases to the Spot Market [5].
Finally, it is computed how much each load pays (or receives as a credit) to the system for that hour.
The proposed methodology and the developed software are based on the flow chart presented in Figure 1.
Section 2 presents the theory background required to compute the Locational Marginal Price (LMP), the Firm Transmission Rights (FTR) and the Optimal

Power Flow (OPF) to determine a re-dispatch to solve the congestion situations.
Section 3 includes a case study considering a network transmission with nine buses. Results are presented and discussed. Finally, in Section 4 the most important conclusions are presented.

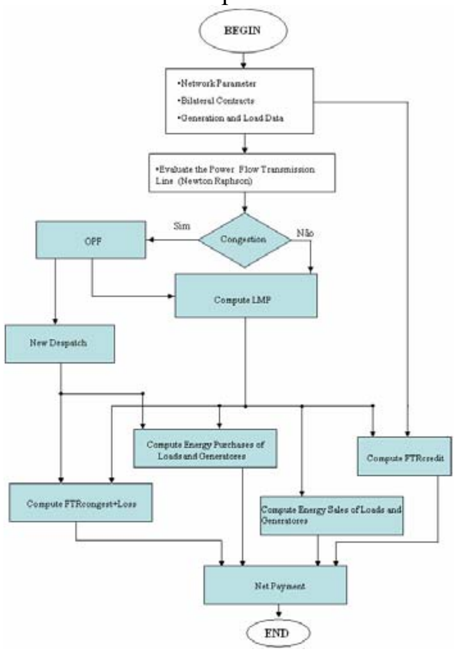

Fig. 1 – General Flow Chart

2 Theory Development

2.1 OPF – Economic Dispatch

In order to evaluate the LMP and to solve the congestion situations, we consider an economic dispatch optimization problem for a snapshot of time t. This can be formulated as follows:

$$\underset{Pgi}{Min} \sum_{i} MC_i(Pg_i)Pg_i \tag{1}$$

Subject to:

$$\sum_i Pg_i = \sum_i Pd_i, \qquad (\lambda) \tag{2}$$

$$Fl^{\min} \leq Fl = \sum_i A_{i,l}(Pg_i - Pd_i) \leq Fl^{\max}, \forall_l, (\mu l) \tag{3}$$

$$Pg_i^{\min} \leq Pg_i \leq Pg^{\max} \ \forall_i, (\gamma_i^{\min}, \gamma_i^{\max}) \tag{4}$$

where:
Pg_i – generation at bus *i*
Pd_i – demand at bus *i*
$MC_i(Pg_i)$ – marginal cost of production or bid function for generator *i*.
Fl – Flow in line l
$A_{i,l}$ – sensitivity of power flow on line l due to injection at bus i.

After solving this optimization problem, the standard locational price for location i and time t is calculated as:

$$\rho_i = \lambda + \sum_l \mu l \, A_{i,l} \tag{5}$$

where:
ρi –Locational Marginal Price of node i
λ – Shadow price associated with equality constraint
μl – Shadow price associated with transmission constraint for line *l*.

2.2 Calculation of Locational Marginal Prices

Locational marginal pricing is a market-pricing approach used to manage the efficient use of the transmission system when congestion occurs on the bulk power grid [5], [10-12].
LMP consists of three components as follows:

$$LMP_i = LMP_{ref} + LMP_{iloss} + LMP_{icong} \tag{6}$$

where:
LMP_{ref} - Incremental fuel cost at the Reference bus (λ)
LMP_{iloss} - Incremental fuel cost at bus *i* associated with losses
LMP_{icong} - Incremental fuel cost at bus *i* associated with congestion.
The loss and congestion components are defined as follows:

$$LMP_{iloss} = (DF_i - 1) * LMP_{ref} \tag{7}$$

$$LMP_{icong} = -\sum_{k \in K} GSDF_{ik} * \beta_k \tag{8}$$

where:
DFi - Delivery factor of bus i relative to the reference bus can be calculated as in (9):

$$DF_i = \left(1 - \frac{\partial P_L}{\partial P_i}\right) \tag{9}$$

GSF_{ik} *or* $A_{i,l}$ - Generation Shift Factor at bus i on line k. This is also referred to as the sensitivity factor relating a change in flow in line k when a 1 MW injection change occurs at bus i
β_k - Constraint incremental cost (shadow price) associated with line k
K - Set of congested transmission lines.

2.3 Economic value of FTR

The Firm transmission right (FTR) is a purchased right that can hedge congestion charges on constrained transmission paths. In other words, it provides FTR owners with the right to transfer an amount of power over a constrained transmission path for a fixed price. Market participants pay congestion charges under a

constrained situation based on LMP differences [2], [5], [9]. When the MWh load value is different from the one contracted, this situation can provoke congested lines and if the generation is not exactly equal to the load, it will require either to purchase or to sell energy to the spot market.
Each FTR holder receives a congestion credit in each constrained hour that is proportional to the FTR value. This credit allocation is based on the initial contract, while the congestion charges are based on actual deliveries.
The FTR credit is computed using the LMP sink and the LMP source, where the LMPsink and LMPsource represent LMPs at starting and ending points of the FTR, respectively [5].

$$\begin{cases} FTR_{cred} = \Pi_{cred} * (LMP_{\sin k} - LMP_{source}) \\ FTR_{cong} = \Pi_{cong} * (LMP_{\sin k} - LMP_{source}) \end{cases} \quad (10)$$

where:

FTR_{cred} – Firm Transmission Right credit.

FTR_{cong} - Firm Transmission Right congestion.

Π_{cred} – Power energy of the initial contract.

Π_{cong} – Power energy based of the new dispatch.

The FTR is equal to the Power energy magnitude times the price difference between the LMP sink point and the LMP source point. The LMPs are based on clearing prices from Day-Ahead Market.
If LMP sink < LMP source, the FTR is liability if FTR is defined as obligation and the FTR has zero value if defined as option.
The FTRs are acquired in three markets mechanisms: Annual FTR Auction, Monthly FTR Auction and FTR Secondary Market.
In order to know how much each participant has to pay, it is necessary to compute the congestion charges and the congestion credits.
After calculating the FTR congestion credits and the FTR congestion charges, it is necessary to evaluate how much energy it is necessary to buy and to sell to the spot market to satisfy the loads. After these calculations, we can evaluate how much the loads have to pay to the system.

$$\begin{aligned} &Net\ Payment = \\ &= FTRcred + (Enegy\ Sold\ to\ the\ spot\ market) - \\ &- FTRcong - (Energy\ Bought\ to\ the\ spot\ market) \end{aligned} \quad \textbf{(11)}$$

3 Case Study

The case study presented in this section uses an example transmission network with 9 buses. It shows how the implemented software evaluates the Firm Transmission Rights, solves congestion problems and calculates Locational Marginal Prices. Finally, it calculates how much the agents have to pay to the system.

3.1 Data

Its line characteristics (resistance, reactance and the maximum limit of power flow) are presented in Table 1.

Table 1 - Line characteristics

Linha		R (p.u.)	X (p.u.)	Cap(MW)
1	2	0,0001	0,200	200
1	7	0,0001	0,200	200
2	3	0,0002	0,300	200
2	7	0,0003	0,250	200
3	4	0,0002	0,100	200
3	5	0,0001	0,300	200
4	5	0,0001	0,200	200
5	6	0,0002	0,260	200
5	9	0,0001	0,100	200
6	7	0,0001	0,400	200
6	9	0,0002	0,300	200
7	8	0,0001	0,100	200
8	9	0,0002	0,200	200

Table 2 presents the contracts of the loads with Generators, the peak load and the Firm Transmission reservations (contracts). The contracts presented in Table 2 are contracts of long term, for example for a year. The set of these contracts does not cause congestion situations.

Table 2 - Contract Generation to Serve Load

Load	Peak Load (MW)	Contracts (MW)	Contracted Generation to Serve Load (MW)
L1	100	100	G2(100)
L2	150	150	G1(50), G3(100)
L3	250	250	G2(150) G3(100)
L5	310	310	G4(270), G8(40)
L6	170	170	G2(30), G4(40) G8(100)
L7	135	135	G2(20), G3(100), G4(15)
L8	350	350	G2(100), G8(50), G9(200)
L9	125	125	G2(100), G4(15), G9(10)
Total	**1590**	**1590**	**1590**

This study case considers the firm transmission rights for an hour. The power generators and the power loads of the initial schedule are presented in Table 3.

Table 3 - Initial schedule

Bus	Generator (MW)	Dec ($/MWh)	Load (MW)
1	100	20	150
2	350	5	150
3	200	10	200
4	340	5	
5	---	---	380
6	250	12	170
7	---	---	250
8	200	5	350
9	200	5	250

In Table 3, Dec is the marginal production cost of each generator.

3.2 Simulation Results

Power Flow calculations

The Power flow calculations are undertaken using Newton Raphson method (Figure 1). The AC power flow is computed not considering the line physical limits. Table 4 presents part of the obtained results: the active power flow and the active losses.

Table 4 - Initial Active Power Flow

Bus	Bus	Flow (MW)	Loss (MW)
2	1	8,4226	0,0333
1	7	218,7926	0,0069
2	3	36,0753	0,0079
2	7	155,5022	0,0584
4	3	92,8207	0,0948
3	5	128,8567	0,0064
4	5	247,1793	0,0514
6	5	34,3203	0,0056
5	9	30,2393	0,0393
6	7	6,4900	0,0023
6	9	39,1896	0,0231
7	8	130,6043	0,0289
9	8	19,4248	0,0005

Congestion Situations

The congestion block (Figure 1) detects if any transmission line are congested. The congested lines in this study case are presented in Table 5.

Table 5 - Congested lines

Bus	Bus	MaxFlow
1	7	18,7199
4	5	47,0900

We can see by the results presented in Table 5 that the power flow in line 1-7 exceeds the maximum limit of this line by 18,72 MW. Line 4-5 has an excess flow of 47,09 MW.

OPF

After calculating the power flow and detecting the congestion situations, for the initial schedule, the software runs the OPF block in order to compute the LMPs and solve the congestion.
The new dispatch, obtained with the OPF, is presented in Table 6.
Table 7 presents the congested lines for the new dispatch (line 3-4, in this study case). For the new dispatch, lines 1-7 and 4-5 are not congested but line 3-4 is now congested. However, the value of congestion of line 3-4 is less than 10 % of the line limit (100 MW), which corresponds to an acceptable overload, so the congestion is considered as solved.

Table 6 - New dispatch

Bus	Generator (MW)
1	0
2	500
3	5
4	395
5	
6	0
7	
8	500
9	500

Table 7 - Congested lines for the new dispatch

Bus	Bus	MaxFlow - Flow (MW)
3	4	2,5018

LMP Calculations

The results obtained to the LMP congestion and LMP loss components are shown in Table 8. The LMP to the reference bus (bus 1) is obtained by the OPF simulation and is equal to 8,9031 $/MWh.
After evaluating the LMP loss, LMP congestion and

LMP of the reference bus components, the total LMP can be calculated as the sum of the three LMP components. Total LMPs are presented in Table 8.

Table 8 – The LMPs

Bus	LMPcong ($/MWh)	LMPloss ($/MWh)	LMPtotal ($/MWh)
1	0,2813	0,2665	9,4509
2	0	0	8,9031
3	-1,0969	0,8118	8,6179
4	3,9032	-1,0639	11,7424
5	1,4644	0,5992	10,9667
6	1,1475	0,5368	10,5874
7	0,5625	0,8889	10,3545
8	0,7819	-0,2731	9,4119
9	1,2207	-0,5957	9,5281

FTR allocated to the loads Calculation

After knowing the Locational Marginal price of each bus, the different FTRs can be easily calculated. For calculating FTRs, it is necessary to compute the transmission congestion charge and the transmission credit charge.

The results obtained to the congestion credit, presented in Table 9, were computed using equation (10) and the initial contracts presented in Table 2.

Table 9 – Cong. credit and cong. charge

Load	Credit($)	Charge($)
1	54.7784	54.7784
2	1.1258	1.4165
3	-42.7725	-42.7725
4	0.0000	0.0000
5	-147.2501	-147.2501
6	121.8762	197.1056
7	181.8595	8.2077
8	27.6422	27.6423
9	30.4460	30.4460
Total	**227.7055**	**100.5000**

The congestion credit value can be negative or positive. The negative values presented in Table 9 represent a bad contract for the load because the LMP of the load bus is higher than the LMP of the generator bus. The congestion credit represents the financial value of the power reserved with the bilateral contracts.

The congestion charges values are presented in Table 9. Congestion charges are the value that each load has to pay. If there is no initial congestion, the FTR congestion charge is equal to zero.

Table 10 shows the energy supplied by the generators to the loads, as in the initial contracts and as resulted from the new dispatch.

After this, it is necessary to verify the energy purchased or sold by the generators and loads to the pool market

Table 10 – Initial contracts and new dispatch

Load	Gen	Contract (MW)	New-dispach (MW)
1	2	100	100
2	1	50	0
2	3	100	4.9675
3	3	100	0
3	2	150	150
5	4	270	270
5	8	40	40
6	2	30	30
6	4	40	0
6	8	100	100
7	2	20	20
7	3	100	0
7	4	15	15
8	2	100	100
8	8	50	50
8	9	200	200
9	2	100	100
9	4	15	15
9	8	10	10

Table 11 shows how much each load has to pay by the purchases in the spot market and it shows the loads and generators sales to the spot market.

Table 11 - Energy Sales and Purchases

Bus	E. Sales ($) (Loads)	E. Sales ($) (Generator	E.Purchases ($) (Load)
1	0	0	427.5
2	0	0	1291.2
3	0	0	430.9
4	0	646.2	0
5	0	0	767.7
6	423.5	0	0
7	0	0	2070.9
8	0	2823.6	0
9	0	2858.4	1048.1
Total	**423.5**	**6328.2**	**6081.3**

After calculating the congestion credit, the congestion charge, the energy sales and the energy purchases, the total value to be paid to the system can be computed using equation (11):

$$Pay = 227.7055 + 423.5 + 6328.2 - 100.5 - 6081.3 = 797.6\ \$ \quad (12)$$

This value must be paid to the system and is calculated as the sum of the total values of Tables 9, 11.
As *Pay* is a positive value, the system will receive, for the considered one hour period, the amount of 797.6 $.
Figure 2 represents the different costs to the initial dispatch and the initial contracts, considering congestion cost (Pay Congestion), the sales of the loads and generators to the spot market (Ger sale pool, load sale pool), the credit due to the contracts (FTRcredit) and the final payment to the system (Pay system).

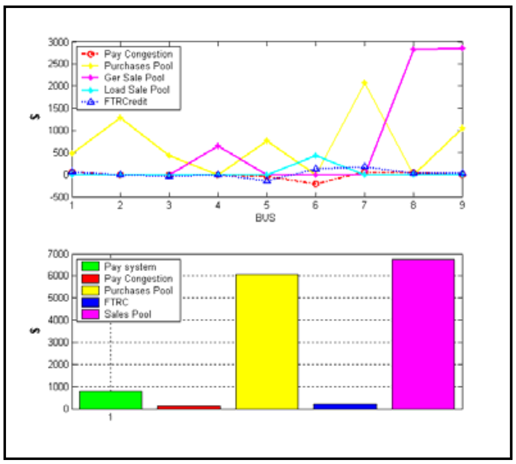

Fig. 2 - Costs for the initial contracts

4 Conclusions

This paper presents a software application to compute Firm Transmission Rights, Locational Marginal Prices and to solve congestion situations in electricity markets. It also determines congestion fees and considers the losses in fee calculations.
This application allows calculating transmission fees strongly connected with physical constraints and power flow, increasing the efficiency of the use of FTRs, as these give correct signs to market agents that use the grid**.**

Acknowledgements

The authors would like to acknowledge FCT, FEDER, POCTI, POSI, POCI and POSC for their support to R&D Projects and GECAD Unit.

References

[1] José Arce, Scott Wilson, "Managing Congestion Risk in Electricity Markets", Carnegie Mellon Conference on Electricity transmission in deregulated markets, 15– 16 December 2004

[2] Ziad Alaywan and Tong Wu "Effects of Firm Transmission Rights on Transmission Revenue Allocation in California", October 2002.

[3] Hung-po Chao, Stephen Peck, Shmuel Oren and Robert Wilson "Flow-Based Transmission Rights and Congestion Management", Electricity Journal, October 2000

[4] Judite Ferreira, "Tarifação em redes de transmissão de energia eléctrica – comparação de métodos e análise dos efeitos de novas interligações" (in Portuguese), MSc Thesis, 2003

[5] Mohammad S., Hatim Y. Zuyi L., "Market Operations in Electric Power Systems", 2002

[6] Juan M. Zolezzi, Hugh Rudnick "Consumers coordination and cooperation in transmission cost allocation" IEEE Bologna Power Tech Conference, Bologna-Italy, June 2003

[7] Janusz W. Bialek, Stanislaw Ziemianek, and Robin Wallace" A Methodology for Allocating Transmission Losses Due to Cross-Border Trades" IEEE Transactions on Power Systems, Vol. 19, No. 3, August 2004

[8] Qiong Zhou, Janusz W. Bialek, "Approximate Model of European Interconnected System as a Benchmark System to Study Effects of Cross-Border Trades", IEEE Transactions on Power Systems, Vol. 20, No. 2, May 2005

[9] Jim Sustman, John P. W. Brown, "The Hidden Cost of LMP: Marginal Losses", Energy Market & Asset Analysis - New energy associates, July 2001

[10] Judite Ferreira, Manuel João D. Gonçalves Zita A. Vale, "Strategic Coalition Impact on Transmission Costs", ICKEDS'04, Portugal, July 2004

[11] Juan M. Zolezzi, Hugh Rudnick "Consumers coordination and cooperation in transmission cost allocation", IEEE Bologna Power Tech Conference, Bologna-Italy, June 2003

[12] PJM Market Development Department, Manual Financial "Transmission Rights Revision", April 2005