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OPF tools for optimal pricing and congestion management in a two sided auction market structure

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Abstract: This paper presents the application to large-scale systems of a new OPF model, which is characterized by the introduction of a two sided auction market structure, with power demand elasticity. This means that the load demand is no longer fixed and each customer presents a demand bid, giving the ISO additional degrees of freedom in managing congestion conditions. The use of the OPF is envisaged in a pool model where the Independent System Operator (ISO) has a centralized dispatch function and he is also responsible for the security and the quality of operation. The ISO runs an OPF to determine the optimal solution, taking into account the network constraints; the byproducts of this optimization are the electricity prices at each bus of the network.

In the competitive environment the opening of the transmission system to the market players is leading more than in the past to congestion conditions, with electricity price volatility and price spikes. In the work we show the capability of the OPF based on a two sided auction structure to furnish to the ISO a solution that reduce nodal price volatility and allows the congestion relief.

A CIGRE 63-bus test system with 5 areas is adopted for an easy comprehension of the usability of the proposed tool. Besides, some important analyses of different scenarios of the Italian market are examined. The results of the investigation put in evidence the presence of bottlenecks in the transmission system in some of the border areas, which limit the TTC of the interconnection with the UCTE networks. The economic signals provided by the nodal price distribution and by the congestion costs are envisaged as useful tools for the Italian ISO (GRTN), Market Administrator (PX or GME) and market players for planning, operational planning and short term operation.

Keywords: power system economics, competitive electricity markets, pool model, demand elasticity, nodal prices, Congestion prices, congestion management.

I. INTRODUCTION

The electricity market evolution from the monopolistic organization of the past to the competitive structures of today is changing significantly the role of the electric system operators [1]. In the monopolistic frame the Central Dispatchers (CD), operating in a vertically integrated environment, were mainly involved in the satisfaction of the user fixed demands at a minimum production cost (economy), while complying operational constraints (security), often themselves establishing the most important limitations in the system management [2]. The aims of preserving the security and the economy of the operation were attained by applying in short and very short term environment the generation schedules obtained by the use of standard security constrained OPF programs with a minimum production cost objective.

In the Pool model [3] the ISO maintains, even if with some limitations, both the CD functions. If a two sided auction market structure [4] with supply offers and demand bids is operating, the ISO uses them to determine the set of successful bidders, whose offers and bids are accepted. The ISO aim is to determine the optimal solution by solving again an *economic dispatch* problem, as CD did, taking into account the network constraints. The violation of any of the various constraints of the system (line flow limits, transformer flow limits, voltage limits, stability limits) causes operational situation defined congestion. The congestion problem can be solved implicitly [5] as part of a new SCOPF model, by determining a security-constrained schedule.

The objective [6] of the optimization problem is the maximization of social surplus. If each generator sets its supply offer equal to its marginal cost it maximizes its profit. Likewise if each load sets its demand bid equal to its marginal benefit it maximizes its net benefit. Under this hypothesis, costs and benefits used to calculate social surplus can be derived from the offer and bid curves (see figure 1).

If we consider a market without operational constraints, the optimum gives a market clearing price and a market clearing quantity and the equilibrium point maximizes social surplus [7]. Considering network constraints, losses and operational limits move the optimum away from the economic equilibrium point and a unique market-clearing price no longer exists. Instead, there are different nodal prices at each bus of the grid. In particular, the presence of network congestion can lead to an unexpected increase of price levels and volatility. The application of a new OPF model, which includes load demand elasticity, is presented with particular attention to the Italian system, where the competition among different production companies is expected for the incoming year.

The paper is organized as follows: in section II a two sided auction market structure is introduced, section III depicts the impact of congestion on electricity markets, while section IV describes in details the mathematical model of the new OPF tool. Section V presents some numerical results on the case studies in order to show the importance of power demand elasticity to smooth congestion costs. This section is dedicated to present the results of the applications to a small test system (CIGRE 63 busses) and to the Italian EHV system in the actual configuration and for a forecasted scenario at the year 2005.

II. THE TWO SIDED AUCTION STRUCTURE

In the new OPF, the demand at each bus can be a variable which depends on the willingness of the customer to pay a certain price for a given level of served load. The power demands at the single bus can be fixed at a predefined value or responsive to the prices of the furnished energy amount (elastic demand).

The willingness to pay of the customer at bus k can be expressed through a positive linearly decreasing function (the demand bid curve) that indicates the unit energy price p_{dk} (marginal price) at which the customer will pay a given amount of power D_k:

$$p_{dk} = p_{dk}(D_k) = p_{0k} + p_{1k} D_k . \quad (1)$$

p_{dk} is the price corresponding to the last unit of power absorbed, and this price applies to all the energy bought. Starting from demand bid curve, the customer benefit function can be obtained as its integral:

$$B_k = B_k(D_k) = b_{0k} + b_{1k} D_k + b_{2k} D_k^2 \quad (2)$$

with $b_{1k} = p_{0k}$ and $b_{2k} = \frac{1}{2} p_{1k}$.

B_k is a function increasing with D_k and is characterized by $b_{1k} > 0$ and $b_{2k} < 0$.

The rationale for connecting the demand bid curve to the benefit function is that in a perfect market a customer would bid its marginal benefit to maximize its net benefit [8].

The supply offer curve $p_{gi}(P_i)$ is a positive linearly increasing price function for the generator at bus *i*:

$$p_{gi}(P_i) = a_{1i} + 2 a_{2i} P_i . \quad (3)$$

The supply offer curve is the only information available to market players, since production costs constitutes *private information*. A particular seller or a group of sellers can exercise market power; in other words they can consistently increase their power supply offers to maintain prices above competitive levels, offering power in a way that does not reflect their true costs [9]. On the other way, if each generator set its supply offer equal to its marginal cost it maximizes its profit.

Under this hypothesis, production costs used to calculate social surplus can be derived from the offer curves. As in the previous vertically integrated structures, the functions $C_i(P_i)$ are quadratic and convex:

$$C_i = C_i(P_i) = a_{0i} + a_{1i} P_i + a_{2i} P_i^2 . \quad (4)$$

The new OPF is characterized by a composite objective function with two terms, the total benefits and the total costs, whose difference represents the so-called *social surplus*:

$$S_s = \sum_{k=1}^{N_e} B_k(D_k) - \sum_{i=1}^{N_g} C_i(P_i) . \quad (5)$$

In the function S_s, N_e is the number of busses with elastic load demand; N_g is the number of generators in the studied system.

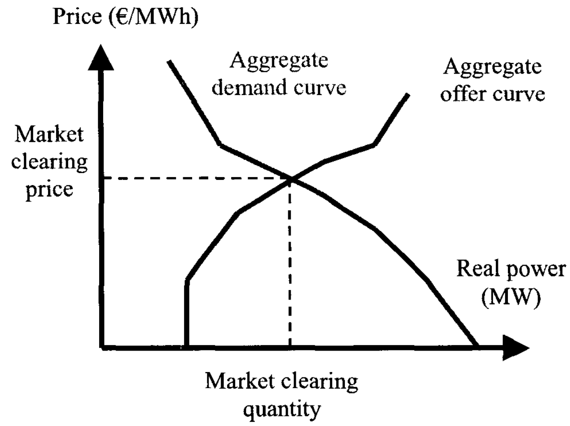

Fig. 1. Market clearing price in an unconstrained and lossless network

III. IMPACT OF CONGESTION

If losses and network constraints are not considered (or they are not active at the optimal point), the solution of the optimization problem is characterized by a certain value of social surplus. The demand prices and the generator prices at each bus are equal. In this situation the market clearing price is unique for the whole system.

On the contrary, if network constraints are considered and some of them are active at the optimal point, congestion can arise causing, along with losses, a different optimum, with a lower level of social surplus. In this situation a market clearing price no longer exists. Congestion may result in certain cases in market price volatility [10] and leads to price spikes. System losses and congestion introduces the *merchandise surplus* S_M:

$$S_M = \sum_{k=1}^{Ne} p_{dk}(D_k) D_k - \sum_{i=1}^{Ng} p_{gi}(P_i) P_i . \quad (6)$$

The demand responsiveness can play a major role in competitive electricity markets, particularly in the case of congestion [11]. There are new degrees of freedom given by the introduction of load demand as an additional decision variable to be considered in the optimization problem.

IV. NEW OPF FOR THE POOL MODEL

Based on the considerations of the previous parts of this paper, a new real power OPF model has been developed: it utilizes as decision variables the vector u of generator offers and demand bids:

$$u = [P_1, \cdots, P_i, \cdots, P_{NG}, D_1, \cdots, D_k, \cdots, D_{Ne}] \quad (7)$$

while maximizing the objective function S_s (the social surplus). Security constraints are introduced as operational limitations on current flows in lines and transformers both in normal states (intact system) and in contingency cases consequent to the outage of single transmission equipment. The solution of the SCOPF is obtained by the use of an iterative quadratic programming algorithm [12] useful to handle very large scale systems as the Italian electric system, where a transition from a monopolistic structure to a competitive market is in act, passing from the unbundling and deregulation phases.

The actual organization based on a passing-through dispatch for the favorite bilateral contracts is going to be transformed in a hybrid structure (pool and bilateral) with ENEL Power, 3 major GENCOS, some NUGs, several IPPs and a single buyer. The acceptance of the generation offers will be based on a merit order list. The ISO, called in Italy GRTN (Gestore della Rete di Trasmissione Nazionale), will be charged of the balance among generation and demand and of determining the optimal and feasible schedules. The SCOPF proposed in the paper for the solution of the ISO problem will furnish together with the loads and generation schedules, the marginal prices in the different busses, whose volatility is consequent to the network congestion.

The price of the energy at a bus n is derived as the variation of the objective function consequent to an increase of 1 MW of real power demand in the bus. It can be evaluated as a linear combination of the Lagrange multipliers of the active constraints at the optimal point with the sensitivity of the right hand sides b_j of the constraints (power flow equations and current limits) with respect to the real power demand D_n :

$$p_{dn} = \frac{\partial F}{\partial D_n} = \sum_{j=1}^{A} \frac{\partial F}{\partial b_j} \cdot \frac{\partial b_j}{\partial D_n} \tag{8}$$

where: A is the number of the active constraints;

$\frac{\partial F}{\partial b_j}$ is the Lagrange multiplier of the constraint j,

$\frac{\partial b_j}{\partial D_n}$ is the sensitivity of the constraint j to the load D_n .

The prices of the energy at a given bus can be associated to the nodal marginal prices, since their definition given in this paragraph.

V. CASE STUDIES AND RESULTS

Simulations performed on two different networks demonstrate the adequacy of the new two sided auction OPF tool to assist the ISO in determining congestion relief and in reducing nodal price volatility.

A. Tests on the CIGRE Network

First, we present numerical results on a CIGRE 63-bus test system, previously adopted by the authors of [13] for applications of optimization techniques to study power system network performances in an open access environment.

The test grid, represented in figure 2, can be divided in five areas, named R, M, F, T, V. The busses of each area are labeled with an integer number with 3 figures, the area code and the voltage level.

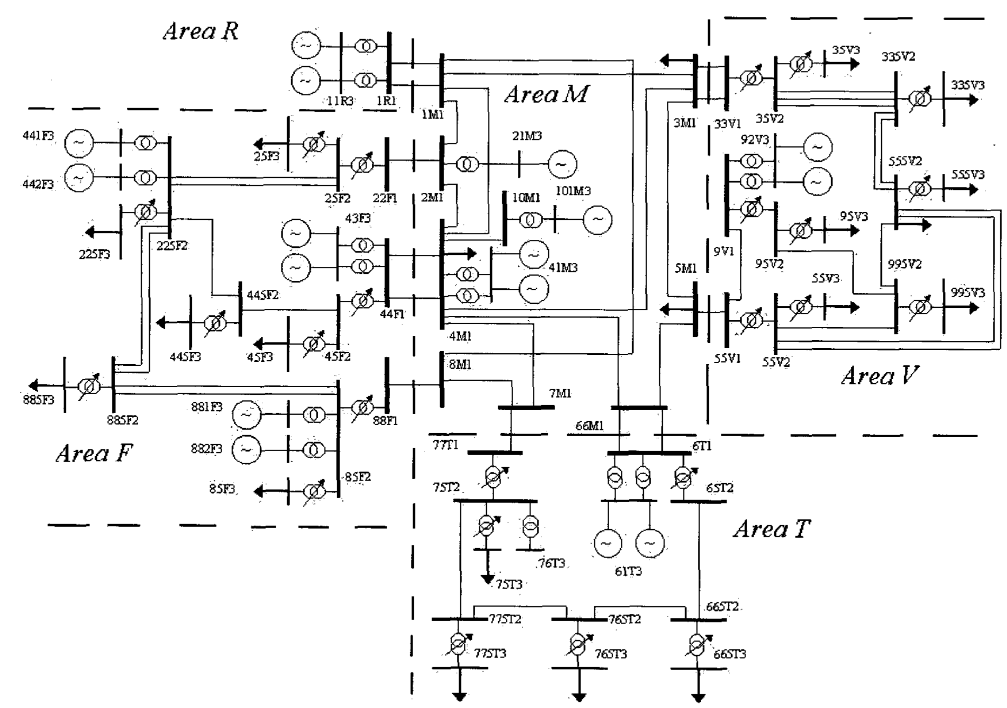

Fig. 2. The CIGRE 63-bus test system

As an example the busses 11R3, 65T2, 9V1 belong to the area R, T and V respectively and are referred to the voltage levels 15 kV, 150 kV, 220 kV. Area R represents an independent power producer, area M is the main grid at 220 kV, areas F, T, V can represent 3 sub-transmission systems at 150 kV with embedded generation. The prices of the generators in the areas R and F are very low, while prices offered in area V are very high. The bottleneck in the system is the line 1M1-3M1 available for the export of the least expensive generations of areas R and F to area V.

First of all, we consider an unconstrained base case and we determine the β dispatch solution. The dependence of the losses on the power injections in the network busses determines the distribution of nodal prices shown in figure 3.

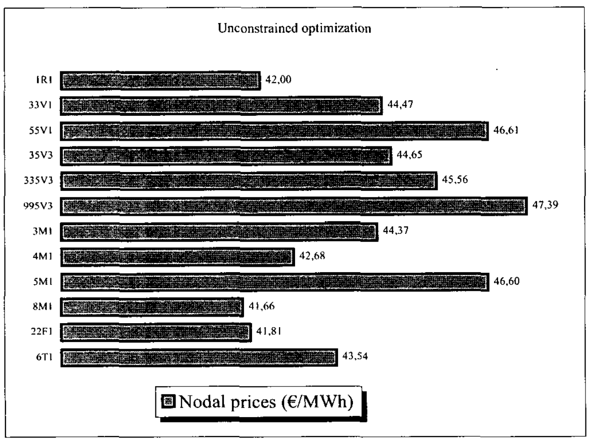

Fig. 3. Impact of losses on nodal prices

The presence of network constraints in normal operation (N security) an in a single contingency constrained case (N-1 security) causes congestion on the line between busses 1M1 and 3M1. The congestion consequently leads to an increase of nodal prices in area V, as shown in figure 4 (for N security) and in figure 6 (for N-1 security).

The effect of a two sided auction market structure on nodal price volatility is shown in figures 5 and 6, for N security optimization and for N-1 security optimization respectively.

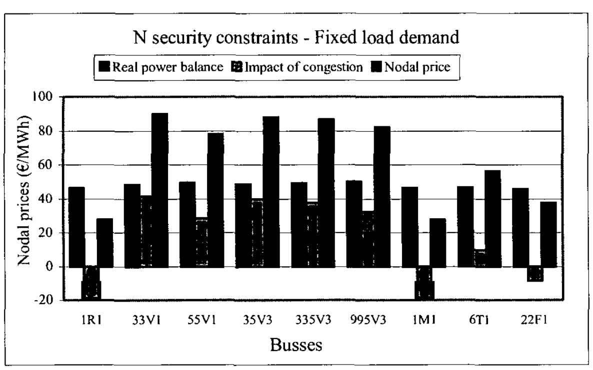

Fig. 4. Impact of congestion due to N security constraints

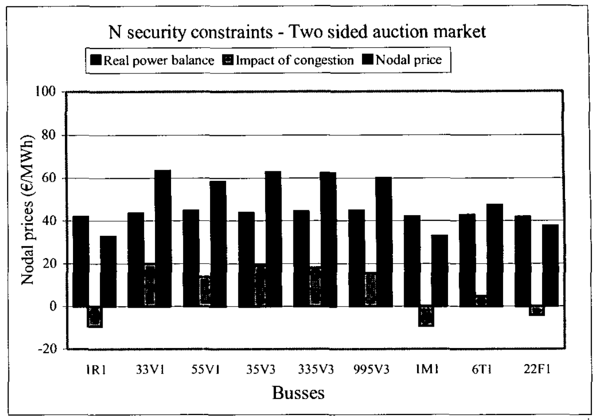

Fig. 5. Reduction of congestion impact in a two sided auction structure

In presence of the N-1 security constraints imposed by the contingency on the line 5M1-66M1, the line 1M1-3M1 is again the most important cause of congestion.

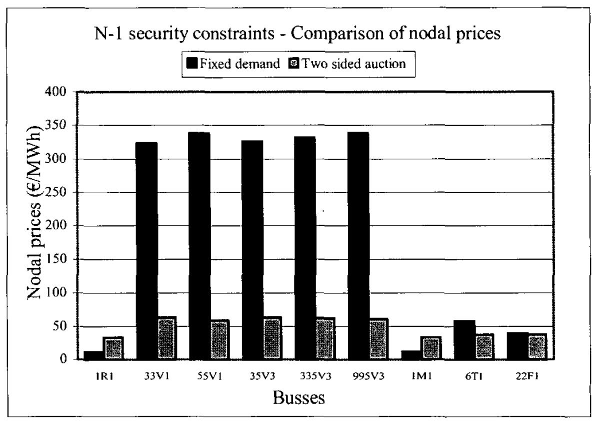

Fig. 6. Impact of congestion due to N-1 security constraints

If the power demand has no responsiveness to electricity market prices, the volatility of nodal prices is extremely higher, as shown in figure 7.

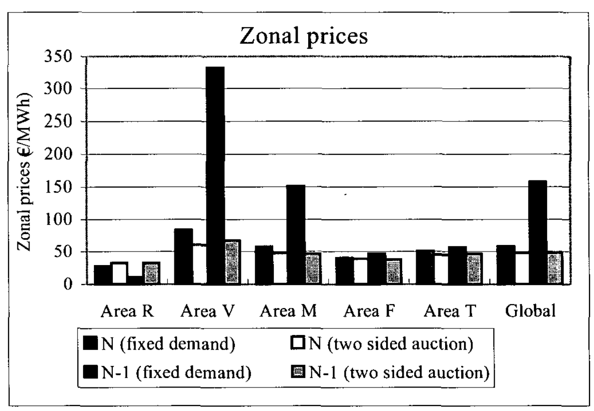

Fig. 7. Comparison of the zonal prices in studied cases

B. Tests on the Italian EHV System

We also used the Italian high voltage grid [figure 8] to study the impact of a two sided auction structure on the electricity market. The system model of the Italian network is a 1200-bus representation, including the interconnections with an equivalent grid of the remaining European system (UCTE). In this network referred to a January 2000 morning peak the load demand reaches about 45 GW, 80 thermal power plants are in operation and the demands of 150 selected busses are responsive to electricity prices. In this situation, the total real power import on the interconnection lines is 5100 MW.

Fig. 8. Italian 380 kV system (January 2000)

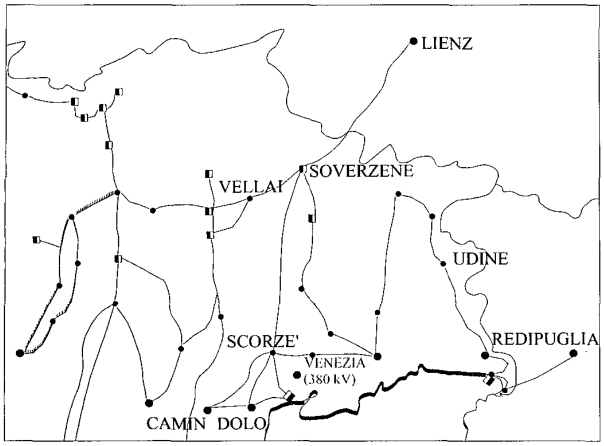

Fig. 9. Particular of Italian 220 kV transmission network (Venice area)

In an unconstrained optimization the nodal prices range from 36,51 €/MWh (in Brindisi) to 39,38 €/MWh (at Bellolampo, near Palermo). The real power losses cause a variation of about 7% in nodal prices.

Introducing the thermal current flow limitations, the most important constraint in the studied case is represented by the 220 kV line Soverzene-Vellai [figure 9] in Venice area (near the Austria border). In the market simulation the congestion increases at a value more than double (83,60 €/MWh) the Vellai nodal price and reduces the Soverzene nodal price to 5,74 €/MWh. To give a term of comparison, the uncongested Venice nodal price is 34,27 €/MWh, while the zonal price for Venice area is 38,78 €/MWh. The presence of a two sided auction market structure, as shown in figures 10 and 11, strongly smoothes this nodal price volatility.

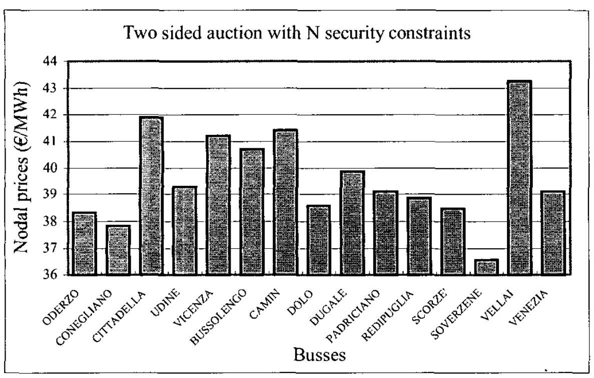

Fig. 10. Reduction of nodal price volatility in Venice area in a two sided auction market

For the old areas (departments) of the ENEL system the zonal prices and standard deviations are evaluated. Zonal prices are obtained by a weighted mean of the nodal prices in each area; in this case the zonal price volatility is very low, with differences under the 4%. Figure 11 shows how much the standard deviation of nodal prices decreases passing from a fixed demand model to a two sided auction structure.

The standard deviation is calculated using "n-1" method:

$$SD_a = \sqrt{N_a \sum_{n=1}^{N_a} p_{dn}^2 - \left(\sum_{n=1}^{N_a} p_{dn} \right)^2 \Big/ N_a (N_a - 1)} \qquad (9)$$

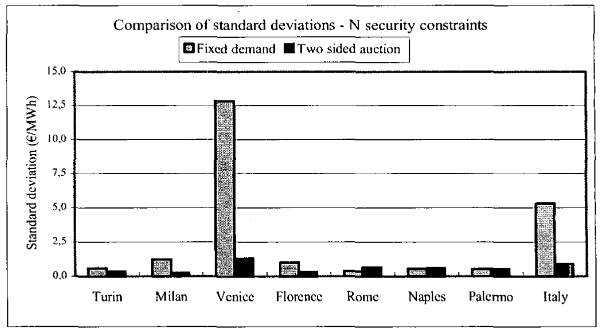

Fig. 11. Comparison between standard deviations

In the N-1 security optimization, the contingency set includes three 380 kV interconnection lines (Venaus-Villarodin, Bulciago-Soazza and Musignano-Lavorgo) and the five most critical outages pointed out by a steady state security analysis program (Bovisio-Brugherio, Bovisio-Turbigo, Soverzene-Scorzè, Ostiglia-Bussolengo in the North and Matera-Laino in the South).

The constraint imposed by the trip of Bulciago-Soazza line congests the near 220 kV interconnection line Mese-Gorduno (Italy-Switzerland intertie) and consequently a 132 kV load island in the North of Milan area, fed by four autotransformers connected to the main grid (Bulciago, Cagno, Cislago and Mese). Table 1 shows the reduction of price volatility in a two sided auction structure.

Table 1. Comparison of nodal price volatility in N-1 security

Bus name	Nodal price (€/MWh)	
	Fixed demand	Two sided auction
Bulciago	73,34	51,82
Cislago	84,70	53,84
Cagno	106,25	51,23
Mese	353,77	97,87
Grandol.	298,72	86,61
Gravedona	294,12	85,68
Grandola	252,29	77,11
Argegno	215,47	69,57
Como Nord	174,82	61,25
Breccia	159,95	58,20
Cucciago	125,09	48,50
Novedrate	107,11	60,43
Salice C.	102,72	59,29
Nibionno	82,53	54,18

With the new OPF we are investigating the TTC of the Italian network for load and generation scenarios pertinent to the year 2005. The characteristics of the scenario discussed in here are an annual load demand increase of 2,5%, the construction of new combined cycle thermal plants. Fuel price are assumed higher than 20% with respect to January 2000. The imported energy prices are assumed lower than the Italian lowest price (coal thermal power plant). A fixed import of 5700 MW causes congestion in the area near the border of the Country: the binding constraint in this optimization is represented by power flow on interconnection line Bulciago-Soazza. The nodal prices distribution in the congested market is depicted in figure 12.

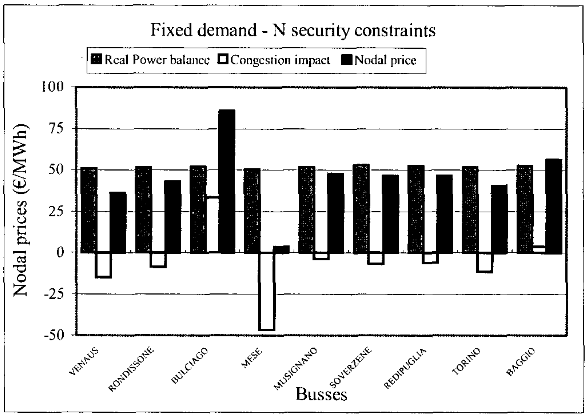

Fig. 12. Congestion impact on prices at a forecasted scenario at year 2005

The N-1 security optimization problem with the same contingency set of the January 2000 case has no feasible solution unless a reduction of the imported power is allowed. Thus, the OPF results seem to be able to furnish, together with the economic signals useful in the short term operation, information on the network expansion planning and on the new generation and load optimal localization.

VI. CONCLUDING REMARKS

In the paper we present a new OPF model, which handles the load demand elasticity in a competitive market. In this framework the load demand is no longer fixed and each customer presents a demand bid, while the new objective function in the optimization problem is the so-called social surplus. The computational tool can assist the Market Administrator, in Italy named 'Gestore del Mercato Elettrico' (GME) to determine the energy optimal pricing in each bus of the network and the ISO to manage congestion problems. Its adequacy is validated by the applications to the Italian EHV system in different scenarios.

It is shown as, if compared to the case of inelastic loads, a two sided auction market structure can strongly reduce congestion costs. The results confirm that the demand responsiveness can play a major role in competitive electricity markets, particularly in case of congestion. In particular in the congested cases the nodal price volatility can be used to send right signals in terms of load curtailability.

Moreover, the simulation tests show as the new OPF can help the ISO, the GME and all the market investors, in terms of financial planning, operational planning and short term operation.

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VIII. BIOGRAPHIES

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Riccardo Vailati received his M.Sc. degree in Electrical Engineering in March 2000 from the Università degli Studi di Pavia, discussing a thesis about the restructuring of OPF tools for the new competitive markets and their impact on power system economics.

Fabio Zanellini received his M.Sc. degree in Electrical Engineering in September 2000 from the Università degli Studi di Pavia., where he is now applying on Ph.D. degree. His research interest is focused on voltage stability and electricity market restructuring.

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