Co-ordinated Auctioning Algorithm for Congestion Management

Konrad Purchala
Electrical Engineering Department
K.U.Leuven, Belgium
kpurchal@esat.kuleuven.ac.be

Thierry Van Craenenbroeck
Electrical Engineering Department
K.U.Leuven, Belgium
craenenb@esat.kuleuven.ac.be

Jozef Van Hecke
ELIA
Brussels, Belgium
jozef.vanhecke@elia.be

Abstract – **Different methods exist to attribute the scarce transmission capacity to the interested market players and to determine the price for the use of it. In this paper the technique of co-ordinated auctioning to solve congestion problems in meshed transmission networks is presented and evaluated with respect to the criteria that are required for a practical implementation. In particular, the application of this auctioning technique in a commercial environment with both bilateral transactions as well as power exchanges at a marketplace is considered. Whereas congestion avoidance using curtailing is straightforward for a given set of bilateral transactions, the method has to be adapted for a market system with nodal bids in which flows cannot directly be attributed to well defined transactions. Coupling schemes can be used to overcome this difficulty. A comparison of different proposals is discussed.**

Keywords: **Congestion Management, DC Loadflow, Power Flow Analysis, Power System Economics.**

1. INTRODUCTION

The European electric power system, originally developed for mutual support and reliability reasons, is gradually becoming the theatre of a marketplace for the commodity called "electrical energy". Several technical problems remain to be solved, and the issue of congested interconnections is certainly one of the more challenging.

Power flows through the cross-border interconnections have to be limited to the maximum allowed value for thermal and stability reasons. Transmission system congestion is a clear indication of the value of the available transmission capacity. In an ideal market, every market player would have to pay a tariff reflecting the full cost he causes to the system. The ultimate outcome of such approach is a system of nodal pricing [1]. However, this mechanism has been considered too complex to be implemented in the UCTE-system, and the decision has been made to use non-distance related transmission tariffs. Consequently, congestion management methods can be considered as remedies for the fact that correct price signals are missing in a transmission tariff.

Single-border capacity auctioning is the simplest way to determine the economic value of an interconnector. As such, this method has already been implemented on different area borders in the UCTE-network (e.g. between The Netherlands and Belgium, The Netherlands and Germany, between Germany and Denmark, …), and is envisaged at other borders.

However, as is shown in the comparison in the next section, this single-border auctioning has also some important drawbacks. These are overcome by the proposed method that can be seen as co-ordinated auctioning. The method itself is explained in section 3, and implementation aspects are discussed in section 4. Finally, the paper is concluded with results from network computations, showing the practical advantage of the method.

2. EXISTING CONGESTION MANAGEMENT METHODS

To be taken into consideration, a congestion management method must comply with several principles such as the prevailing legislation, the structure of the power market and the correct treatment of existing contracts. At the Florence Regulators meeting of November 1999 [2] five criteria were upheld to evaluate congestion management methods:

- fair and non-discriminatory;
- economically efficient;
- transparent;
- feasible;
- compatible with the market structure.

With respect to these criteria, a short overview of existing methods is given.

2.1. *Pro-rata rationing*

In this method all transactions on a congested interconnection can be carried out partially, by the ratio of the existing NTC (Net Transfer Capacity, defined as the Total Transfer Capacity, TTC, minus the Transmission Reliability Margin, TRM) to the total requested capacity. No incentive is given to any of the market players (neither to system operators nor to system users). Even worse, the method may very likely induce unwanted behaviour such as gaming, organised by market players overestimating their capacity needs.

2.2. *Priority-based rules*

The most common method uses the chronological ranking of the reservations until the NTC is completely reached and subsequent reservations have to be denied (first come - first served principle). It certainly favours long-term planning and does not leave enough room for short-term action, creating a sluggish market, except when a fraction of the NTC is deliberately set aside for short-term contracts. The main drawback, however, is again that the method does not convey any economic incentive to market players.

Another possible solution is to compute the contributions of the transactions to a specific congestion by determining the physical flow induced by a transaction on the congested line. Curtailment is then based on the relative contributions (highest contribution is curtailed first).

A third possible priority rule is based on energy prices. It gives priority to the most economically efficient market participants, and doing so, provides a strong signal for further system use. Generators with the lowest bid price are allocated capacity first, and on the load side, the highest price offers are granted. Contrary to the pro-rata rationing and the first two priority-based mechanisms, this is a non-transaction based method, which can only be used in an organised power market. As a matter of fact, the mechanism can be considered as an implicit auctioning where electric energy and capacity are coupled.

2.3. Market splitting

Market-splitting is based on the price elasticity of the electric energy. It needs a single power market to be implemented. If congestion occurs between two geographical areas separated by one or more interconnections, the power market is split up. Market logics imply that a higher pool price is obtained in the region downstream of congestion, whereas a lower pool price is achieved in the upstream area. Consequently, the congestion is relieved through the market mechanism itself. The congestion charge, being the difference between the clearing prices in both areas, is collected by the market operator. This type of method is already implemented in the Nordic market. It is considered to be economically efficient, both on short-term (run or stop decision) as on long-term basis (relocation of generating facilities and loads), but requires a spot market. With congestion reflected by zonal pricing, the difference between these prices can also be considered as the corresponding transmission tariff.

2.4. Redispatching and countertrading

This method involves redispatching of generating units based on the price information that generators communicate to the TSO for modulating their output up and down. It has an advantage of making congestion cheaper since more generators compete for necessary modulating power. On the other hand, it requires strong co-ordination between the TSO's involved.

Countertrading is based on the same principle of generation adjustment, but this method imposes the TSO's to go on the market and actually buy and sell the electricity on both sides of the interconnector. This makes the adjustment price more transparent but conflicts with the goal of unbundling.

Redispatch and countertrading can be considered as remedial actions. Contrary to auctioning and market splitting, these methods do not directly give an incentive to the market. The TSO's have to intervene and mitigate congestion [3]. On the other hand, this does give incentives to the TSO to reduce congestion. Instead of generating revenues, the remedial methods imply additional costs that have to be recovered. In its evaluation [2], ETSO has concluded that these methods comply with the principle of economic efficiency.

2.5. Single-border capacity auctioning

Transmission capacity auctioning ignores the underlying electric energy contract. Market participants offer a price for the capacity and the bids are stacked in descending order until the NTC is completely filled up. As for the energy market, a distinction can be made between the clearing price and the pay-as-bid price. This method shares economic efficiency with methods described in subsection 2.3 and 2.4, and has proven to work well with different types of trade or even market organisations.

However, in a strongly interconnected system such as the European UCTE-network, this approach might not work, or at least be suboptimal for various reasons [4]:

- difference between auctioned quantity and corresponding physical flow crossing the border;
- risk of non-convergent interactions between different clearing processes when handled separately and successively;
- poor quality and inconsistency of the economic signals resulting from these processes.

Therefore, in virtually the same way as the co-ordinated redispatch extends the principle of an isolated zonal redispatch, the auctioning approach can be extended to a co-ordinated variant in which an optimal solution for the system can be obtained, giving efficient and consistent signals to all market players. This is the underlying idea of the method proposed in [4] and further developed in this paper.

3. CO-ORDINATED AUCTIONING

The TSO's organise jointly a simultaneous auction of the capacity available on the tie lines between zones. For simplicity, only one auctioning round is assumed, although market participants may be in favour of a variant with several rounds, since this gives an early price indication. The proposed method is applicable when different slices of the total available capacity are allocated in different auctioning rounds.

The bids may come in pairs (from a given input zone to another off-take zone) for bilateral transactions or individually in a power pool environment. The equality constraints are the network equations complemented with the expression keeping the balance between generation and load, whilst the inequality constraints are the mathematical formulations of the available transmission capacity. The optimisation process determines a set of bids giving the highest economic value to the auctioned transfer capacity, under abovementioned constraints. This problem is easily rearranged as a set of equations solvable by a standard Linear Programming (LP) routine.

Though rather easy from mathematical point of view, the most reluctance for the practical implementation may reside with the market players, claiming that the method suffers from lack of transparency. To overcome this problem the published NTC's can be completed with a table of PTDF's (Power Transfer Distribution Factors). These indicate how much a given interconnection will be loaded by the use of a transmission right. This information may help the system user in determining the bids to submit.

It should also be explicitly mentioned that the method as proposed supposes full netting of the transits. This has as important consequence that only physically independent bids between the actual generation and the actual load location can be accepted. To illustrate the point: if trader A makes a bid from X to Y, with at the receiving side trader B making a bid from Y to Z, without physical generation and load at Y, the auctioning method would fail when accepting the bid from Y to Z, and not the one from X to Y. In that case, B would not be able to realise his bid. So, when the Y to Z transaction on a congestioned line would be in the decongestioning direction, the fact that it cannot be realised might cause additional congestion beyond those foreseen by the co-ordinated auctioning mechanism. The fact that only physical bids are allowed could be a major obstacle in accepting of this method by traders.

4. IMPLEMENTATION ASPECTS

4.1. Mathematical constraints

The problems of transmission losses, voltage support by reactive power injection and congestion management are considered to be auxiliary services. Therefore, the system of network equations for congestion management analysis can be derived as a set of dc loadflow equations. This system is very easy to solve, since all equations are linear.

For every node i the following equation must be fulfilled:

$$P_{G,i} - P_{L,i} - P_i(\delta) = 0 \tag{1}$$

where:

- $P_{G,i}$ power generated at node i;
- $P_{L,i}$ power taken at node i;
- $P_i(\delta)$ power leaving node i.

For every line the transmission capacity imposes an inequality constraint:

$$B_{ij}(\delta_i - \delta_j) \le P_{MAXij} \tag{2}$$

where:

- B_{ij} admittance between nodes i and j;
- δ_i voltage angle at node i;
- δ_j voltage angle at node j;
- P_{MAXij} power limit for the interconnector i-j.

4.2. Transaction-based explicit bidding

In the transaction-based explicit bidding approach, all bids represent bilateral contracts between producers and consumers. They consist of an origin, destination, quantity and price. The system of equations (1-2) is completed with so called "market separation constraints", added to ensure that the TSO does not interfere with energy contracts between generators and consumers. For every bid b, the following equation should hold:

$$P_{G,b} - P_{L,b} = 0 \tag{3}$$

This approach can easily be modified if bids are aggregated by scheduling co-ordinators. An optimisation program is used aiming at maximizing the value of the transmission capacity:

$$\max \sum_b \left(C_b . T_b\right) \tag{4}$$

where:

- C_b bid price of bid b;
- T_b allocated power quantity of bid b.

If congestion occurs, some bids are curtailed or denied in the auctioning procedure. Since these bids represent possible transactions, a corresponding reduction takes place both at generator and load sides.

In this approach it is very easy to charge for congestion. The clearing price is the marginal price for capacity of the congested line. In a single-border capacity auctioning it would be done by checking the price of the cheapest bid allowed (or partly curtailed) – this bid would set the line price. In co-ordinated auction however, a more rigorous approach is needed because of the flows interdependence. The correct method is to use shadow prices (marginal variation of the objective function with respect to transmission constraint). These shadow prices immediately result from the optimisation of the LP-solver. Once the price is settled, bids contributing to saturating a given bottleneck i-j are detected. The flows caused by these bids and induced on the congested line can easily be computed. They correspond to a fraction $F_{b,ij}$ of the bid quantity. The congestion charge $CC_{b,ij}$ is then the product of the induced flow and the marginal price of the capacity:

$$CC_{b,ij} = F_{b,ij} . T_b \cdot MP_{ij} \tag{5}$$

This can be done for every congested line separately, yielding the total congestion charge for the bid b.

4.3. Non-Transaction-based explicit bidding

The system of unilateral bids is more flexible for market players. They do not have to care about finding counterparty. They just declare power injections and power off-takes at a given area. It is the role of the market operator to keep the power system balanced.

However, charging for congestion is more complicated in a non-transaction based approach. In the clearing process, the cheapest generator bids and the cheapest load bids are curtailed (if necessary). Since there are no bilateral contracts, it is not possible to determine the path of the flow induced by a bid. There is no information about which bid causes congestion. Some scheme must be developed to couple the bids in generation-load pairs.

Four variants are discussed:

- distance-based coupling;
- optimisation of non-constrained bids;
- transactions with a psychical hub;
- proportional coupling.

Coupling based on electrical distance between the bids can be realised by examining the Zbus matrix. Every generator bid is coupled with the closest load bid.

Following this procedure, the power flow path for a given bid is reduced to a minimum. In its present form, the bids are taken one by one until they are fully coupled. However, this approach has some drawbacks. The final couples may be very unrealistic. An overall minimisation of electrical distance may be more appropriate.

Optimisation of congestion charges is based on the idea to treat bidders in a similar way as in the transaction-based approach. There, the curtailed bids had to pay a full value of their bid. Here, congestion charges are being optimised in such a way, that the overall payment of non-curtailed bids is as little as possible. Constrained bidders would have to pay the rest (overall congestion charge, being a product of power flowing through the line and its marginal price, is constant after the auction), but not more than their initial bid.

In the third approach, artificial contracts with a hub are created – every generator gets artificial load at the hub node and every load get artificial generation. Based on such contracts, congestion charges are derived using exactly the same procedure as in the transaction-based approach (bilateral bids). Drawback of such approach is that the numerical results heavily depend on the choice of the hub node. However, one might say that a different hub implies a different product (the right to withdraw energy from or deliver to the hub), and the nodal prices of energy will accordingly vary. If perfect competition is assumed, market players will react to a change of hub (change of product) implying a change of energy price and the shifts in congestion charges could thus be justified. In such a case this approach would be similar to Market Splitting.

A fourth method also uses the concept of hub, but without geographically defining its position. It can be seen as a sort of virtual or dispersed hub approach, avoiding the problems of preferential treatment of some bidders, associated with the choice of the hub. Coupling is proportional - every generator is to certain extend coupled with every load. It is the simplest of all proposed solutions and might prove to be the most effective.

It must be stressed here, that once the bids are coupled, the pricing strategy is the same as it was for a transaction-based approach. Generators and loads cover the congestion charge together, e.g. proportionally based on the bid prices. However, specified ratios such as a fixed 50-50 or 25-75 can also be adopted.

5. NUMERICAL ANALYSIS

Transaction- and non-transaction-based approaches are analysed using a simplified European network model. In the example, power flow is determined by a DC loadflow, including full netting of opposite flows. It must be stressed, that using PTDFs netting can also be achieved, by introduction of negative coefficients in the participation matrix. The transfer capacity between countries, represented with one-node areas, has been fictitiously put at 1500 MW. In the example the power flow is determined by a DC loadflow, thus including full netting of opposite flows.

5.1. *Transaction based approach*

The contracts assumed in the example, and the corresponding allocation results are shown in Table 1 and on Figure 1.

Tab. 1. Transaction-based auction: data and results.

Bid	In	Out	Bid quantity [MW]	Bid price [€/MW]	Allocated quantity [MW]	Paid price [€/MW]
T1	B	NL	800	12	800	-4.47
T2	F	NL	350	14	350	11.39
T3	CH	D	200	10	200	1.39
T4	**F**	**I**	**1900**	**14**	**788.6**	**14**
T5	F	B	1000	18	1000	15.86
T6	F	CH	1500	10	1500	-2
T7	**CH**	**I**	**3300**	**16**	**2534.32**	**16**
T8	CH	A	400	12	400	-8.30
T9	D	CH	1800	8	1800	-1.39
T10	D	A	200	10	200	-9.69
T11	A	I	250	10	0	0
T12	**D**	**NL**	**1800**	**12**	**1650**	**12**

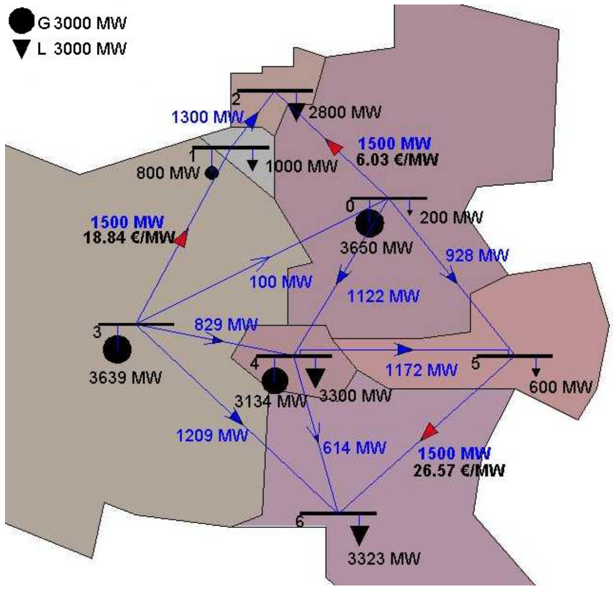

Fig. 1. Transaction-based co-ordinated auction results.

There are three congested lines, each one having a different price (Fig. 1). These prices reflect exactly the value a given line represents to the market. It may seem that these values are higher than the ones offered by market players. However, the clue is that every market player pays only for a fraction of its bid – the part of its allocated power that flows through a congested line. In that way the price a market player is willing to pay for one MW is never exceeded. The curtailed bids pay exactly the amount they have offered. This is logical, since market players are bidding depending on the value the transmission system represents to them. They are willing to pay a given price for the right to exploit their contract – to transfer energy from point A to B. If a bid were curtailed, this would mean that he is willing to pay less than the others are. He would be "last accepted", and therefore he would have to pay his full bid price. For the others there would be a surplus of money - they would not have to pay their full offer, which is in accordance with the marginal pricing principles.

When the price to pay is negative, the market player will receive a bonus for relieving congestion in the system. This assumes that the transactions will effectively be carried out (full netting). Otherwise, the market player has to be penalised, because the missing counterflow that his expected transaction was going to provoke, may induce more congestion in the system. If use-it-or-lose-it principle were adapted, receiving of congestion bonus would not be possible, because of uncertainty of opposite flows.

This method does not allow any gaming by splitting up bids. If e.g. the bid T4 is split into two bids, 1500 MW @ 14 €/MW and 400 MW @ 15 €/MW, the total congestion charge paid by this market player remains unchanged.

5.2. Non-transaction-based approach

Here only unilateral bids are considered. For the sake of ease the same quantities of power as in the previous case are assumed, but split into generation and load bids. The transaction bid price is split equally. The nodal bids represent now the value the market player is willing to pay for being able to inject or withdraw a given amount of power. In this approach, faced with unilateral bids only, there are two problems to solve when charging for congestion. First is to find the price of the line capacity. The other is to determine the power flow induced on a congested interconnector by every bid separately.

Shadow prices give immediately the solution to the former problem. The value of the transfer capacity is equal to the dual price of the line capacity constraint (Figure 2). For the latter problem there must be a good, non-discriminating method to couple the bids. The comparison of such methods is shown in Table 2.

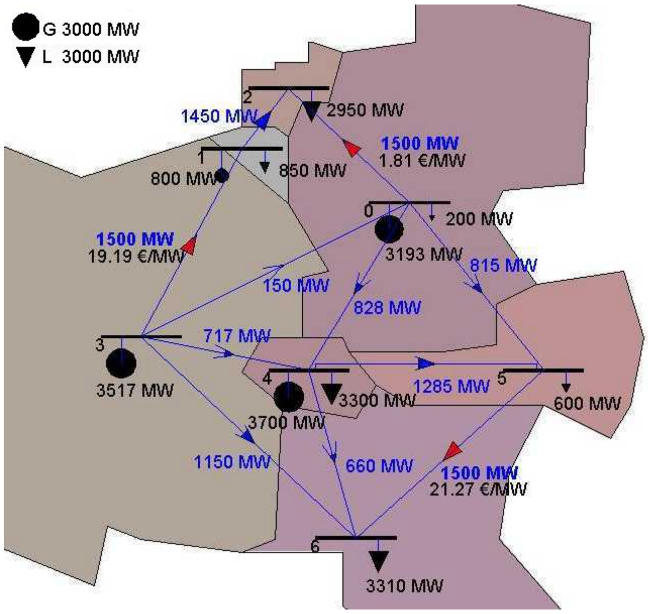

Fig. 2. Non-Transaction-based co-ordinated auction results.

Tab. 2. Non-Transaction-based auction: data and results for different coupling approaches.

Bid	Location	Bid price [€/MW]	Quantity [MW]	Transactions with hub in Germany		Transactions with hub in Italy		Allocated quantity [MW]	Charges minimization	Zbus based coupling	Proportional coupling
				Allocated quantity [MW]	Paid price [€/MW]	Allocated quantity [MW]	Paid price [€/MW]		Paid price [€/MW]	Paid price [€/MW]	Paid price [€/MW]
G01	B	6	800	800	-9.00	800	-8.36	800	-0.86	0	-4.09
L01	NL	6	800	0		**649.994**	**6.00**	800	4.92	4.30	3.83
G02	F	7	350	350	4.38	350	5.00	350	-0.47	5.12	3.07
L02	NL	7	350	350	6.00	350	6.00	350	5.22	4.60	4.14
G03	CH	5	200	200	1.55	200	4.93	0			
L03	D	5	200	200	0.00	200	-4.00	200	0.00	0.21	-0.07
G04	F	7	1900	1900	4.38	1900	5.00	1900	-0.44	4.89	3.07
L04	I	7	1900	**383.506**	**7.00**	1900	0.00	**9.97603**	**5.94**	**6.86**	**5.57**
G05	F	9	1000	1000	4.38	1000	5.00	1000	5.15	4.25	3.47
L05	B	9	1000	**800.015**	**9.00**	1000	8.36	**849.995**	**7.80**	**0.46**	**7.39**
G06	F	5	1500	1500	4.38	**25.5862**	**5.00**	**266.82**	**4.31**	**-0.37**	**2.54**
L06	CH	5	1500	1500	-1.55	1500	-4.93	1500	-0.31	-0.08	-0.82
G07	CH	8	3300	3300	1.55	3300	4.93	3300	3.74	-0.37	3.70
L07	I	8	3300	3300	7.00	3300	0.00	3300	4.35	6.67	5.93
G08	CH	6	400	400	1.55	400	4.93	400	0.67	-0.91	3.19
L08	A	6	400	400	-5.00	400	-7.55	400	-2.94	-2.96	-4.07
G09	D	4	1800	1800	0.00	**1159.36**	**4.00**	**1193.15**	**3.11**	**3.67**	**1.81**
L09	CH	4	1800	1800	-1.55	1800	-4.93	1800	-0.22	0	-0.72
G10	D	5	200	200	0.00	200	4.00	200	-0.97	4.23	2.09
L10	A	5	200	200	-5.00	200	-7.55	200	-3.04	-3.03	-3.69
G11	A	5	250	**178.55**	**5.00**	0		0			
L11	I	5	250	0		250	0.00	0			
G12	D	6	1800	1800	0.00	1800	4.00	1800	4.19	4.71	2.33
L12	NL	6	1800	**1561.99**	**6.00**	1800	6.00	1800	4.43	4.11	3.83

A main issue in examining the feasibility of the proposed methods is to check the prices market players have to pay. Those must not exceed the initial bids. In transaction-based approach we learned, that if a bid were curtailed, price per MW would equal the bid price.

As shown in Table 2 the results of the “transactions with the hub” approach are heavily dependent on the choice of the hub. Not only congestion charges differ, but also so does the power allocation. Bids located at the hub are favoured over the rest. They are always accepted, no matter how low their bid price is. The corresponding loadflow pattern can therefore differ with the change of a hub node, even thought the same set of bids is analysed. However, as stated earlier, this method can only be really evaluated when also taking into account nodal energy prices.

All three remaining methods have the same power allocation and loadflow pattern (Figure 2). Congestion pricing is performed after power allocation. Generators and loads cover congestion charges proportionally, depending on their bid price. If a G- and L-bid having different prices were to be coupled, the cheaper bid would pay less than the more expensive one. Thanks to that strategy no market player is charged more than his initial bid - the asked congestion charge does not exceed the value offered for transmission rights.

The results of the coupling approach based on Zbus, show a peculiarity: in a special case a constrained player can be coupled in such a way, that he receives a congestion bonus for his activity (like generator bid G06 – see Tab. 2.). This is illogical and the fact that it can occur is a serious drawback for this mechanism.

Minimisation of congestion charges is an LP subproblem. Extra constraints can thus be added in order to prevent a coupling, where prices to pay exceed the initial bid prices, or where curtailed players receive money for their activity. In this approach congestion charges for all non-constrained players are to be minimised. Constrained bidders cover the remaining charges. Although congestion charges acquired with this method are acceptable, the method is vulnerable to gaming. If a market player split his bid into many smaller ones, he might be able to significantly reduce his congestion payment.

In proportional coupling (virtual hub), the congestion charges are paid proportionally by every market player (because bids are coupled proportionally – every generation is to some extent coupled with every load). There is no situation where a player has to pay more than his offer or where a constrained player receives a congestion bonus. Nor is there any discrimination of bidders related to the arbitral choice of the hub node or distinction between curtailed and non-curtailed players.

This last method seems to be the best, because of its simplicity, transparency and lack of discrimination. Optimisation of congestion charges may be a good idea, but it adds to the complexity of the method, and can be subject to gaming. Creating artificial contracts with a hub is also a good, transparent method, but in co-ordinated auctions for capacity, no information concerning energy prices is available. Therefore, it is not explicitly evident if differences in hub-dependent congestion charges are compensated with differences in energy prices.

6. CONCLUSIONS

This paper has developed the mathematical framework of the co-ordinated auctioning, a mechanism that is very suitable for solving congestion in a highly meshed transmission network. The method complies with the criteria of a good congestion management method. A special advantage over other economically efficient methods is its easy integration with different types of trade and market organisation. On the other hand however, no incentives are given to the TSO who is being rewarded as long as congestion occurs. Good regulation is therefore required to avoid unwanted TSO manipulation.

This paper has first dealt with bilateral transactions, for which the approach is a straightforward optimisation with constraints. This basic method has then been adapted for use with unilateral bids. Therefore, the proposed solution is to combine individual bids into virtual transactions. Four variants are discussed. All of them are suboptimal, but the proportional coupling seems to be acceptable for both market players and TSO’s. The results prove that this may be an efficient way of pricing transmission capacity under congestion. The proposed method is based on full netting.

The implementation of this mechanism requires a high-level of co-operation and information exchange between the different TSO’s. It might be advisable to implement it on a regional basis first and learn from the experience, before extending the scope.

REFERENCES

[1] W.W.Hogan, “Contract networks for Electric Power Transmission”, Journal of Regulatory Economics, vol.4, pp.211-242, 1992.

[2] ETSO, "Evaluation of congestion management methods for cross-border transmission," Report at Florence Regulators Meeting, Nov. 1999.

[3] L.J. de Vries: “Capacity Allocation in a Restructured Electricity Market: Technical and Economic Evaluation of Congestion Management Methods on Interconnectors, Proc. of IEEE Power Tech Conference, Porto, 2001.

[4] ETSO, "Co-ordinated Auctioning of Transmission Capacity in Meshed Networks," Discussion Paper, March 2001.

[5] P.R.Gribik, G.A.Angelidis, R.R.Kovacs, “Transmission Access and Pricing with Multiple Separate Energy Forward Markets,” IEEE Trans. on PWRS, vol. 14, pp. 865-876, Aug. 1999.