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TRANSMISSION PRICING OF CROSS-BORDER TRADES IN EUROPE

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Abstract: In this paper application of the tracing methodology to the transmission pricing of cross-border trades in Europe has been introduced. The methodology was shown to exhibit the following features: (i) it requires only limited amount of information with no information required about individual transactions; (ii) transmission prices can be calculated in a decentralised manner with only neighbouring countries exchanging information; (iii) transmission charges are based on the actual physical flows and are therefore cost-reflective; (iv) the transmission revenue is exactly recovered; (v) the scheme retains the subsidiarity principle; (vi) the methodology is simple, transparent and very fast; (vii) the methodology can deal with circular flows.

1 INTRODUCTION

Electricity production in the EU has for decades been based on monopoly production and 15 separate, national markets. Community Directive 96/92/EC adopted unanimously by all EU countries on 19 December 1996 has brought about a long-awaited change. The directive will, over a period of time, allow all large and medium sized purchasers of electricity to choose their suppliers freely from throughout the EU. As from 19 February 1999, at least 26% of national demand has to be open for competition and all customers of more than 100 GWh must be permitted to choose their supplier.

In this context it is quite astonishing that, although the liberalised market has already started to operate, no rules have been approved with respect to the fundamental question of how to account for transmission effects of cross-border trades of electricity. Among many transmission problems, two are probably the most important as they can make or break the electricity market: (i) accommodation of all the transactions within the available transmission capacity; and (ii) appropriate transmission pricing mechanisms.

The issue of technical accommodation of all requested trades has long been recognised as one of the stumbling blocks on the road to the liberalised market. Bottlenecks (constraints) in the transmission network may create a congestion when it is necessary to curtail (constrain-off) some of the trades in order not to exceed the system security limits. A dramatic example has been provided in 1997 when the experiment with a zonal pricing system in the Pennsylvania-New Jersey-Maryland Interconnection (PJM) collapsed as soon as the system became constrained [1]. Also in Europe, in August 1997, the Belgian system became severely constrained due to significant flows from France to Netherlands which was caused by a chain of contracts not including the Belgian TSO [2].

The issue of transmission pricing is also very important as it links the commercial and technical side of the electricity trading. A proper transmission pricing regime should satisfy a number of requirements which are often contradictory [3].

The EC has recognised the importance of transmission [4] and they have commissioned an independent study to evaluate the different proposals [2], but it's been published well after the market has started. At the time of writing this paper, no agreement on common rules has been reached. This failure presents a serious obstacle to the development of the common electricity market in Europe.

This paper will concentrate on the issue of transmission pricing only. The existing transmission pricing schemes will be shortly reviewed and a possible application of the electricity tracing methodology [5,6] for the cross-border trades in Europe will be presented.

2 TRANSMISSION PRICING

Economic theory stipulates that the net welfare of the society is maximised when the prices are equal to the marginal costs. F. Schweppe et al [7] developed the nodal pricing methodology based on that principle, from which the optimal transmission prices can be derived [8]. However the marginal transmission pricing, although theoretically optimal, seems to suffer from the following disadvantages: (i) it does not provide enough revenues to compensate the transmission system owner [9]; (ii) it is very complicated and non-transparent; and (iii) it may not be politically implementable in Europe as in effect it would also have to be used for internal transmission pricing in the member states. This issue is quite politically sensitive as this would contradict the principle of subsidiarity. Also probability of all member states agreeing to the same intra-system transmission pricing is rather low.

The two simple alternatives to the marginal pricing are the postage stamp and the contract path pricing. Postage stamp methodology is the simplest as it allocates a uniform pro-rata transmission price to all the transactions without regard to the location of the buyer and the seller. As such, the methodology completely neglects any transmission effects.

The contract paths methodology works as follows. If there is a contract from country A to country B, the two countries determine arbitrarily the physical paths on which the electricity flows. In fact, however, electricity flows on a number of physical paths which usually are not properly reflected in the contract path agreement. This phenomenon is called the *loop* or *parallel flows*. For example, the mentioned earlier congestion in the Belgian system in 1997 happened because the specified contract paths did not take into account that a large amount of contracted power between France and Netherlands flowed actually through Belgium. Thus, although very attractive from the point of view of simplicity and easiness of application, the contracts path methodology is widely believed to be a fiction endangering the secure operation of the power system.

In preparation for the market opening, a working group of European Transmission System Operators (TSOs) prepared a draft paper on their proposal for the cross-border trades [10]. According to their methodology, each country would specify three components of the transmission cost: component G applied to all generation within a country; component L applied to all load demand within a country; and component T applied to all transfers both within and between countries.

How each country defines and derives those fees is a matter of subsidiarity. The fees can be postage-stamp or geographically differentiated. The example used in [10] shows how the methodology can be applied to international transactions by estimating the *effect* of a given transaction on the interconnected transmission system. A number of interesting points can be made with respect to this example.

1. The methodology requires analysing the effect of every single transaction. This requires intensive exchange of information between utilities and also may be opposed on the grounds of commercial sensitivity.
2. In order to model the effect of a given transaction a quite detailed model of the whole interconnected system is required. If the number of transactions is large (as it is expected to be), the analysis of all the transactions can be very time consuming.
3. The methodology may not satisfy the transmission revenue recovery requirement as the charging is based on considering the *effect* of individual transactions. If the effect is non-linear, e.g. as it is the case with losses, the revenue recovered may be greater or smaller than required.

The aim of this paper is to show how the tracing methodology can be accommodated within the framework proposed by the European TSOs [10]. It is important to appreciate, however, that the tracing methodology is general and not limited to the framework proposed by the European TSOs.

3 TRACING AS APPLIED TO THE PROPOSAL BY EUROPEAN TSOs

Conventional wisdom says that it is impossible to trace the flow of power from individual generators to individual loads in meshed transmission networks. Recently however, a novel approach has been developed that challenges this view [5,6]. Assuming that at any network node the inflows are distributed proportionally between the outflows, it is possible - by following the acyclic directed graph of flows in the network - to trace how real and reactive power flows in the lines from individual sources to individual sinks. The proportionality assumption can be justified using the cooperative game theory [11]. Tracing methodology can be seen as a compromise between economically optimal marginal pricing and simple averaged (postage stamp) pricing [11]. In order to demonstrate how the methodology can be accommodated within the Proposal by the European TSOs, an example analysed in [10] will be now considered.

The system diagram is shown in Figure 1. Each of the bigger circles represents a national network connected by tie-lines to other networks. The numbers on the diagram represent some assumed actual (metered) real power generations, demands and tie-line flows. For simplicity, transmission losses have been neglected although they can be easily included. It will be assumed that all the transmission costs are to be allocated to the loads but the methodology can be easily modified to charge both generators and loads at some predefined ratio.

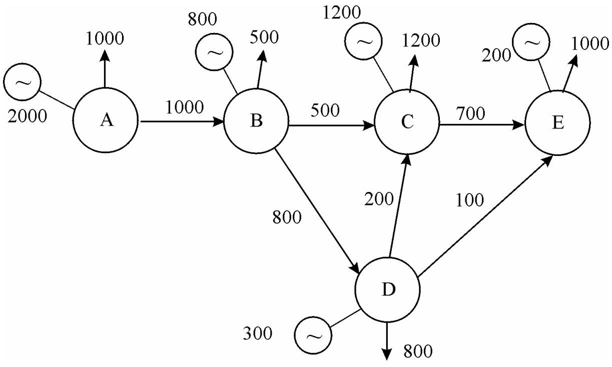

Figure 1 Example system.

Only the allocation of the transit charge (component T) will be discussed in this paper as the allocation of the G and L components is straightforward. The G charges are obtained simply by multiplying the local generation by the local G charge whilst the L charges are obtained by multiplying the local demand by the local L charge.

The assumed transmission prices in Euro/kW are as follows. Country A: 2, country B: 8, country C: 4, country D: 4, country D 4. For simplicity it will be assumed that the transit charge is allocated to the loads only but the algorithm can be easily modified to allow sharing of the transit charge between the generators and the loads at some pre-defined ratio.

Following tracing methodology, transit charges are passed down, following the flows, starting from the head node of the directed graph (country A). At each node the costs are distributed proportionally between the outflows and passed down the network until the last (tail) node of the directed graph is reached (country E). Note that this methodology is entry/exit based, i.e. a transaction from A to B will be charged the entry (generation) fee at A and the exit (load) fee at B.

It can be argued that for a fair cost allocation, the injections to each individual network have to be netted out by subtracting demand from generation. In this way agents in a transit network (like network C in Figure 1 which has a balanced internal generation and demand) will not be charged for cross-border trades. Netting out the injections will give a system shown in Figure 2.

Let us treat the flows shown in Figure 2 as a directed graph of flows and apply the electricity tracing methodology. As the injections have been netted out, the algorithm will give charges due to cross-border trades only. On top of these, there will be also some charges for internal transmission within each country – these will be calculated later.

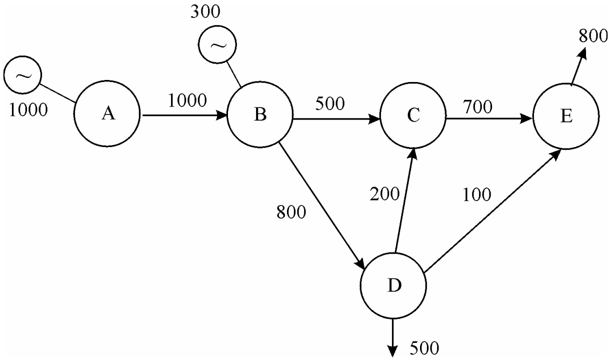

Figure 2 Example network with netted out injections.

The tracing algorithm can be executed by a series of recursive calculations starting from the head node of the directed graph (country A) and finishing with the tail node of the graph (country E) – see discussion to [6] and [11]. The same goal can be accomplished using a matrix approach [5]. The advantage of the matrix approach is that it is more amenable to computer programming and it allows formal tools to be applied for the numerical analysis of the algorithm. It can be shown that the matrix approach is computationally equivalent to the recursive approach if the network nodes are processed according to their order in the directed graph of flows. The matrices involved are then triangular and they can be solved using recursive forward or backsubsitution [6,11].

The total power transmitted over a supernode i, P_i, is equal to the sum of the load in i, P_{Di}, and power outflowing from the supernode in tie-lines to other networks:

$$P_i = \sum_{l\in\alpha_i^{(d)}} \left|P_{i-l}\right| + P_{Di} = \sum_{l\in\alpha_i^{(d)}} c_{li}P_l + P_{Di} \quad \text{for } i = 1,...,n \qquad (1)$$

where $\alpha_i^{(d)}$ is the set of networks supplied downstream directly from network i, $c_{li} = \left|P_{l-i}\right|/P_l$, and n is the number of networks in the interconnected system. This equation can be re-written as

$$P_i - \sum_{l\in\alpha_i^{(d)}} c_{li}P_l = P_{Di} \quad \text{or} \quad \mathbf{A_d P} = \mathbf{P_D} \qquad (2)$$

where $\mathbf{A_d}$ is the $(n \times n)$ *downstream distribution matrix* and $\mathbf{P_D}$ is the vector of network demands. The (i,l) element of $\mathbf{A_d}$ is equal to

$$\left[\mathbf{A_d}\right]_{il} = \begin{cases} 1 & \text{for } i = l \\ -c_{li} = -\left|P_{l-i}\right|/P_l & \text{for } l \in \alpha_i^{(d)} \\ 0 & \text{otherwise} \end{cases} \qquad (3)$$

Note that $\mathbf{P} = \mathbf{A_d^{-1}P_D}$ and its i-th element is equal to

$$P_i = \sum_{k=1}^{n} \left[\mathbf{A_d^{-1}}\right]_{ik} P_{Dk} \qquad \text{for} \quad i = 1,2,\ldots n \qquad (4)$$

This equation shows how power transmitted over a network, P_i, is distributed between all the loads in the system. Hence the transit charge due to cross-border trades allocated to load k can be expressed as the sum over all the i networks of the contributions to load k multiplied by the transit charge T_i:

$$\text{Allocation to load } k = \\ = \sum_{i=1}^{n} \left[\mathbf{A_d^{-1}}\right]_{ik} P_{Dk} T_i = P_{Dk} \sum_{i=1}^{n} \left[\mathbf{A_d^{-1}}\right]_{ik} T_i \qquad (5)$$

while the revenue collected by TSO in network i can be calculated as:

$$\text{Revenue for transits in network } i = \\ = \sum_{k=1}^{n} \left[\mathbf{A_d^{-1}}\right]_{ik} P_{Dk} T_i = T_i \sum_{k=1}^{n} \left[\mathbf{A_d^{-1}}\right]_{ik} P_{Dk} \qquad (6)$$

Substituting (4) into (6) will show that the revenue collected by the i-th TSO is equal to P_iT_i , i.e. the total revenue allowed.

3.1 System with netted out injections

For the system shown in Figure 2 vector $\mathbf{P_D}$ is [0 0 0 500 800]', vector $\mathbf{P}$ is [1000 1300 700 800 800]', and matrix $\mathbf{A_d}$ is

```
1.000 -0.7692       0      0        0
    0  1.0000 -0.7143  -1.00        0
    0       0  1.0000      0   -0.875
    0       0 -0.2857   1.00   -0.125
    0       0       0      0    1.000
```

Application of equations (5) and (6) gives the allocation of transit charges due to cross-border trades shown in Table 1. Rows correspond to charges incurred, and collected by the TSO, in a particular network while the columns correspond to the allocation to a particular load.

Clearly the loads in countries A, B, and C incur no transit charges as countries A and B are net generators while country C is just a transit country with balanced internal generation and demand. Tracing the flows on the graph reveals that country D is supplied only via countries A and B while country E is supplied via all the other countries.

Table 1 Charges due to cross-border trades (netted-out injections).

Network	load A	load B	load C	load D	load E	Total
A	0	0	0	769	1231	2000
B	0	0	0	4000	6400	10400
C	0	0	0	0	2800	2800
D	0	0	0	2000	1200	3200
E	0	0	0	0	3200	3200
Total	0	0	0	6769	14831	21600
per kW				14	19	

Table 1 shows only the charges due to cross-border trades. Additionally there will be charges to those loads which are deemed to be supplied by internal generation in a given country (i.e. those which have been cancelled out by internal generation when the netted out injections in Figure 2 have been obtained). These loads will be paying to their TSO the transfer charge equal to the internal demand (assumed to be covered by the internal generation) multiplied by the internal transfer charge. Thus the total transfer fees collected by the TSOs are obtained by adding these charges to the charges shown in Table 1- see Table 2.

Table 2 Total transfer fees collected by TSOs (netted out injections)

TSO in network	Internal transfer fee	Cross-border transfer fee	Total
A	1000x2	2000	4000
B	500x8	10400	14400
C	1200x4	2800	7600
D	300x4	3200	4400
E	200x4	3200	4000

It can be easily checked that the total transit charges payable to each TSO are equal to: (total transmission over the country x T charge). Hence the requirement of recovering the transmission revenue is fulfilled.

How the charges due to cross-border trades (shown in the last row in Table 1) and those due to internal system demand (second column in Table 2) are allocated to individual loads in each country is again a matter for subsidiarity. The simplest option is to charge all the loads within a country the same averaged charge and these are shown in Table 3.

One can however argue that a better cost-reflectivity is obtained when the charges due to cross border trades are levied only on the loads with import contracts (as only their imports cause the transits) while the internal transfer charges (second column in Table 2) are charged only to the loads without import contracts. In this case note that the per kW charges for the importing loads in D and E (14/kW and 19/kW, respectively) are quite high compared to the charges for the non-importing loads in the same countries (4/kW). This is due to a longitudinal character of the system where the imported power has to travel a long distance. Therefore the pancaking effect is quite strong.

Table 3 Averaged transport charges (netted out injections).

Charge	load A	load B	load C	load D	load E	Total
total	2000	4000	4800	7969	15631	34400
per kW	2	8	4	10	16	

3.2 System without netting out injections

It is interesting to compare the results of charging with netted out injections shown in Figure 2 with the case when the original generations and demands are analysed, as in Figure 1. Table 4 shows the result of applying equations (5) and (6) to calculate the transfer charges to the flows shown in Figure 1. Note that these charges have to be allocated to all the loads, both importing and non-importing, as they take into account both internal and cross-border transfers. When comparing with the netted-out injections considered previously, Table 4 should be compared with Table 3.

Table 4 Total transfer charges (injections not netted out)

Network	load A	load B	load C	load D	load E	Total
A	2000	556	453	647	345	4000
B	0	4000	3261	4655	2484	14400
C	0	0	4800	0	2800	7600
D	0	0	505	3200	695	4400
E	0	0	0	0	4000	4000
Total	2000	4556	9020	8501	10324	34400
per kW	2	9	8	11	10	

The charges given in columns can be justified by inspecting the directed graph of flows in Figure 1. Load A is the head of the graph so it incurs only the local transfer charge equal to the product of the demand and the T charge (1000x2=2000). The loads in country B are deemed to be supplied partially locally and partially from A. Similarly the loads in country C are deemed to be supplied partially locally and partially from A and B. The loads in D are being supplied locally and from A and B while the loads in E are being supplied from all the countries.

Note that the transfer charges are much more uniform now as the effect of imports is averaged over more loads. Compared with Table 3, the per kW charges have been substantially reduced for the loads in country E but the charges have gone up for all the loads upstream from E, apart from country A. The per kW transit charge for loads in country A is without a change as A is at the head of the direct graph of flows. The per kW charge for loads in B and C is much higher than when the injections were netted out, as the loads in B and C are now deemed to import some power from countries upstream in the directed graph of flows.

It can be easily checked that the sum of transmission revenues in a given country given in the last column in Table 4 is the same as before.

The general conclusion is that applying the tracking methodology without netting out injections averages the transfer charges over more loads in the interconnected network. This reduces the pancaking effect but may cause objections from the transit countries not participating in the exchange, like e.g. country C.

4 CIRCULAR FLOWS

One of the problems connected with the practical implementation of the tracing algorithm is the problem of circular flows. These circular flows may be present when the sub-systems of the interconnected network are represented by single supernodes. Consider for example the flows shown in Figure 3 which correspond to three subsystems with a 50 MW contract from A to B and where the circular flows could be caused by geographical separation of generators and loads in subsystem A.

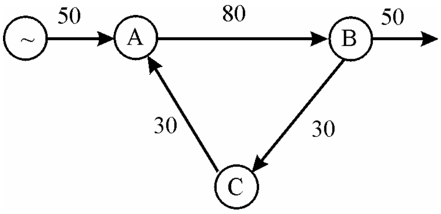

Figure 3 Example of circular flows.

In this case the graph-based algorithm fails as there is no head node of the directed graph (where all the line flows start from) or the tail node (where all line flows finish) but the matrix-based algorithm provides a meaningful solution. The downstream distribution matrix and its inversion are:

$$\mathbf{A}_d = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -30/80 & 0 & 1 \end{bmatrix}, \quad \mathbf{A}_d^{-1} = \begin{bmatrix} 1.6 & 1.6 & 1.6 \\ 0.6 & 1.6 & 1.6 \\ 0.6 & 0.6 & 1.6 \end{bmatrix}$$

and the allocation procedure to the loads will show that load D should pick up the charges not only for the A-B transfer of 50 MW but also for the circular flow of 30 MW. This is entirely logical as load B is the only load in the network so it must pick up all the charges. This result may seem to be unfair to load D as it corresponds to an implicit assumption that the import of power from A to B is also responsible for the circular flows. This may generally not be the case. Therefore it seems that a fairer cost allocation is obtained when it is assumed that the allocation of transmission costs due to the circular flows is done separately to that due to import/export contracts. This means that the digraph shown in Figure 3b can be seen as a superposition of two digraphs shown in Figure 4: acyclic digraph corresponding to import/export contracts shown in Figure 4a and a purely cyclic graph corresponding to circular flows shown in Figure 4b.

The transmission cost allocation due to export/import contracts can be done according to the tracing methodology executed using the acyclic digraph shown in Figure 4a. The cost allocation due to circular flows shown in Figure 4b can be done in at least two ways. The simplest way is to assume that the circular flows are an inherent feature of interconnected networks so that the transmission costs due to circular flows have to be shared between affected utilities. The other possibility is to undertake an extensive load-flow study using full models of the affected utilities in order to determine which utility is causing the circular flows and should therefore be charged for them. However this may prove to be a contentious issue.

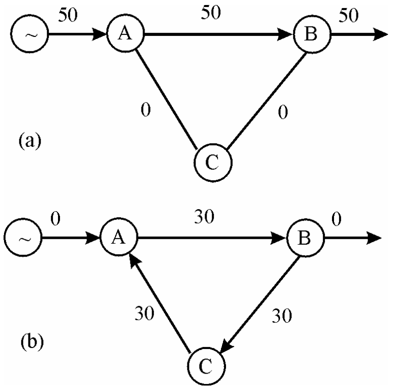

Figure 4 Cyclic digraph decomposed as a sum of: (a) acyclic digraph; (b) purely cyclic digraph.

5 IS THE EUROPEAN TSO NECESSARY?

Implementation of the tracing methodology requires knowledge of all the tie-line flows and generations/demands in all the countries. This information is usually available because tie-line flows are monitored for AGC purposes while the generations and demands have to be measured for billing purposes. However the scheme still requires someone to collect all the information and do the calculations. In other words a mini European TSO, if only for transmission pricing purposes, would be necessary. Although one could argue that for system security purposes such a TSO is necessary anyway, the member countries may be opposed to this idea mostly for political reasons. In order to overcome this obstacle, a possibility of implementing the tracing scheme which does not require existence of the European TSO would be advantageous. In order to do that one should notice that the graph-based recursive scheme satisfies this requirement. The calculations are performed step by step with the information being passed down from the head of the directed graph downstream until it reaches the tail of the graph. At each step communication only between neighbouring utilities is required. Hence the whole calculation can be executed in a completely decentralised way.

Obviously the same methodology can be applied when the matrix approach used in this paper. First of all note that matrix equation (2) is sparse and its structure is similar to that of the upper half of the admittance matrix. Thus it can be formed in a decentralised manner as each TSO needs to know only the flows in its tie-lines. When the nodes are ordered according to their order in the directed graph of flows, the resulting $\mathbf{A_d}$ matrix is upper triangular [6,11]. Hence it can be solved in a decentralised manner by recursive backsubstitution. The computational steps are then identical to those of the graph-based algorithm

The disadvantage of the approaches outlined above is that although the solution can be obtained in a decentralised manner, it is sequential, i.e. a given TSO can only do its bit of calculations when all the TSOs upstream have finished theirs. This can be easily implemented using a simple checking algorithm. The matrix approach, however, also allows a decentralised approach in which the calculations can be done in parallel using one of the parallel methods of solving linear equations, e.g. Jacobi method. At each calculation step all the TSOs can do their calculations independently from each other and then exchange the result with their neighbours.

6 CONCLUSIONS

In this paper application of the tracing methodology to the transmission pricing of cross-border trades in Europe has been presented. The methodology exhibits the following features:

1. The data required are internal generation and demand, which are usually quite accurately metered for billing purposes, and the flows on tie-lines which are also usually quite accurately monitored. No information is required about individual transactions between loads and generators. This limits the amount of information to be shared between individual TSOs and also prevents disclosure of commercially sensitive information about individual contracts.
2. Transmission prices can be calculated in a decentralised manner with only neighbouring countries exchanging information.
3. The transmission charges are calculated based on the actual physical flows and are therefore cost-reflective.
4. The scheme allows the transmission revenue to be exactly recovered.
5. The scheme retains the subsidiarity principle according to which each country is free to apply whatever methodology it wishes for internal transmission pricing purposes.
6. The methodology is simple, transparent and very fast.
7. The methodology can deal with circular flows (i.e. when the directed graph of flows contains cycles).
8. The charges are quite stable [11].

The question still remains whether or not the injections should be netted out. It seems that netting out injections, as in Figure 2, is fairer to the customers in transit networks but may result in a strong pancaking effect. By comparison, when the injections are not netted out as in Figure 1, the methodology is simpler, the pancaking effect is reduced but the approach may be seen to be less cost-reflective.

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