Multiarea Transmission Network Cost Allocation

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***Abstract*—This paper deals with the problem of transmission cost allocation (TCA) in very large networks with multiple interconnected regions or countries. The basis of one scheme recently put forward is a single-area TCA algorithm from which inter-regional compensations are computed. One concern about this approach is that an international operator (IO) must have access to detailed information that autonomous regions or countries may not be willing or able to share. This led to the development of a new multiarea TCA scheme, called multiarea decoupled (MAD), in which each region carries out its own TCA, while the IO carries out a region-wise TCA on the network of tie lines. In MAD, the IO does not require detailed and possibly proprietary information about regional networks, relying only on the characteristics of the tie-line network and the extent to which each region uses such a network. This is a key issue, especially in North America, considering FERC's intention to provide Regional Transmission Organizations (RTOs) with exclusive autonomy to provide transmission service and to set and administer their own transmission-use tariffs. Numerical studies on the proposed scheme are described, including a four-area system based on the IEEE reliability test system (RTS) network.**

***Index Terms*—Equivalent bilateral exchange, flow based, multiarea networks, proportional sharing, tie lines, transmission cost allocation (TCA).**

I. INTRODUCTION

THIS paper deals with the problem of transmission cost allocation (TCA) in power systems with multiple interconnected geographically dispersed areas or regional transmission organizations (RTOs).

This problem could be solved by treating the multiarea network as if it were a very large single area and applying conventional single-area TCA schemes [1], [3], [4]. However, there may be practical and political impediments to the exchange of regional network cost and load flow data across autonomous areas.

Notwithstanding these potential difficulties, a multiarea TCA scheme was recently proposed combining the following three steps [2]: a) An international operator (IO) with access to cost and transmission network data on all elements in all regions runs a single-area flow-based TCA accounting for the use of all transmission elements by all generating and consuming agents across the full interconnected network; b) based on the results of step a), the IO assigns inter-regional and local network use charges among all regions. Similarly, each region is charged for its use of the network of tie lines; c) each region distributes the combined tie-line, inter-regional, and local use charges among its local generators and consumers in a *pro rata* manner.

This general scheme, to which we assign the acronym MAX,[1] is being proposed for use in the European Union [6]. The implementation of the MAX scheme brings up a number of concerns.

1) The IO that coordinates the overall TCA process must be kept up to date on the cost and impedances of all transmission equipment across the continent. The requirement to share such data is cumbersome if not impossible in very large systems with multiple independent transmission organizations. In North America, this prerequisite could be in conflict with FERC's aim to grant increased autonomy to its RTOs, including the independent administration of transmission-use tariffs [5].
2) The initial step calls for detailed transmission-use charges to be calculated for all network elements in each region by all individual agents in all other regions. As an example, the charges for a generator in Germany would be calculated not only for the use of local lines but also for the use of transmission equipment in a country as distant as Portugal. However, as discussed next, these detailed charges are not applied in this form. Thus, a single generating unit in Germany would not be sent a bill for the use of a line in Portugal, as in single-area schemes. Instead, the German system would receive a bill for the use of the Portuguese network that the German operator would then allocate internally in a *pro rata* manner. One can, however, question the desirability of starting with detailed transmission-use allocations over the entire network only to have this information condensed into coarser interarea payments.

This paper proposes an alternative multiarea transmission cost allocation scheme with the acronym MAD[2] that respects regional autonomy. Its main steps are as follows.

a) Each region carries out a local TCA among its generators and loads based on local network and cost data. Importing and exporting tie lines are treated as virtual generators and loads, respectively. The IO is kept out of this step and does not require access to detailed regional information. Furthermore, under MAD, each area has the autonomy to choose its local TCA method.
b) Each region allocates a fraction of its regional network cost to each of its loads and generators as well as to each

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[1] The letters M and A in MAX stand for multiarea, while X stands for exact in the sense that the IO needs exact detailed network and cost data across all regions.

[2] MAD stands for multiarea decoupled.

of its importing and exporting tie lines. The amounts allocated to the tie lines are reported by the regions to the IO who appends them to the regulated tie-line costs to define the so-called *tie-line augmented costs*.

c) Each region is then reduced to a single node with a single generator and demand representing the corresponding area totals. The augmented tie-line costs are then allocated by the IO to each area according to its use of the network of tie lines. In this step, as in the regional allocation of step a), the IO also has the option to choose a preferred TCA method. The IO then allocates a supplementary charge to each net area generation and demand for the use of the tie lines, which is distributed by the area regional operator among its generators and loads in a *pro rata* manner.

The principal benefits of the proposed MAD approach are as follows.

- Each regional operator (RO) requires detailed access to its internal technical and cost data only. Each region carries out its own transmission cost allocation following local rules.
- The IO requires access only to data about the tie-line network interconnecting the regions.
- Some exchange of data is required between the ROs and the IO, but this data exchange is very limited under MAD compared to the complete data exchange needed to implement MAX. Under MAD, each RO must only communicate to the IO the fraction of the cost of its regional network use by the tie lines connected to this region. In turn, the IO must only communicate to each region its share of the cost of using the international or inter-regional network of tie lines.
- The choice of the TCA approach for tie-line use is left to the discretion of the international operator.

In what follows, the multiarea network cost allocation scheme MAD is developed in detail based on the equivalent bilateral exchange (EBE) principle [1], summarized in the Appendix for easy reference. This implementation of the MAD scheme is applied to two case studies, including a four-area version of the IEEE RTS 96 system and compared to a single-area TCA.

II. DECOUPLED MULTIAREA TCA BASED ON EQUIVALENT BILATERAL EXCHANGES

We now present the details of the MAD approach using the EBE principle (see the Appendix) for the TCA of both the regional and tie-line networks. This approach is applied ex-post, which means that the transmission-use charges are defined after each market settlement period, thus reflecting the real use of the transmission equipment, including random or scheduled outages.

The entire network is assumed to be subdivided into na areas interconnected by a number of tie lines. An area can be a country, an RTO, or a traditional control area. The MAD methodology comprises four main steps.

1) *Allocation of local network costs*: The cost of the local area transmission networks is allocated among four different types of equivalent bilateral exchanges:
   a) between local generators and local demands;
   b) between local generators and exporting tie lines;
   c) between importing tie lines and local demands;
   d) between importing and exporting tie lines.
2) *Calculation of augmented tie-line costs*: The cost allocated to the EBEs of type a and to the corresponding area generators and demands follows the EBE approach, as described in the Appendix. In addition, for each tie line, the costs for local area use allocated to the EBEs of types b and c are reported by the regions to the IO, who then appends them to the respective regulated tie-line cost, thus defining the *augmented tie-line cost*. In case d, one half of the cost allocated to the EBE cost is assigned to the importing tie line and the other half to the exporting tie line. The rationale for passing on these costs to the tie lines is that the costs represent the fraction of the total area cost associated with the use of this area by exports and imports. An illustrative example of this step is detailed in Section III.
3) *Allocation of augmented tie-line costs*: The augmented cost of the tie lines is allocated to the areas according to the single-area EBE principle. Here, the areas are represented as single nodes interconnected through an equivalent network of tie lines. The equivalent bilateral exchanges are now defined between areas rather than between buses and are termed AEBEs. The AEBEs represent exchanges between the total generation and the total consumption in each area, information which is available to the IO.
4) *Final allocation among all generators and loads*: The augmented tie-line costs allocated to the AEBEs are distributed among the net generators and loads in each area also following the EBE principle. These supplementary allocations are added to those already assigned in step 1) due to local regional use by local exchanges.

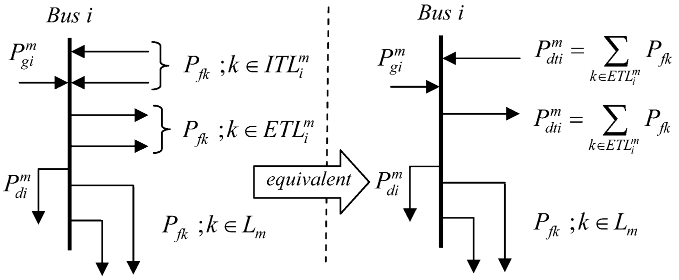

Fig. 1. Power balance at boundary bus i of area m.

These four steps plus some revenue reconciliation issues are now described in detail.

1) Allocation of Local Network Costs: First, for each transmission area m, we identify the tie lines that import into bus i (set ITL_i^m) and those that export from bus i (set ETL_i^m). In addition, the set L^m defines all lines inside area m. The flow of power in an arbitrary line k is denoted by P_{fk}.

Fig. 1 now shows a boundary bus i in area m with its generation and demand P_{gi}^m and P_{di}^m, local area flows P_{fk}, $k \in L_m$, and importing and exporting tie lines, respectively, P_{fk}, $k \in ITL_i^m$ and P_{fk}, $k \in ETL_i^m$. The figure also shows the equivalent net imports and exports, respectively, $P_{gti}^m = \sum_{k \in ITL_i^m} P_{fk}$ and $P_{dti}^m = \sum_{k \in ETL_i^m} P_{fk}$.

We next define and calculate the use of each area by all area generators P_{gi}^m, all area loads P_{di}^m, as well as by the net imports P_{gti}^m and the net exports P_{dti}^m. This local area use is found following the EBE principle by first defining the four possible types of equivalent power exchanges for each area.

a) Between local generators and local demands

$$GD_{ij}^m = \frac{P_{gi}^m P_{dj}^m}{P_d^m}, \qquad \forall i, j \in B^m \tag{1}$$

where B^m stands for the index set of all buses in area m, including boundary buses, and where P_d^m is the net demand in area m, including net exports, defined by

$$P_d^m = \sum_{i \in B^m} P_{di}^m + \sum_{i \in BB^m} P_{dti}^m \tag{2}$$

with BB^m being the index set of boundary buses in area m.

b) Between local generators and exporting tie-lines

$$GT_{ij}^m = \frac{P_{gi}^m P_{dtj}^m}{P_d^m}, \qquad \forall i \in B^m, j \in BB^m. \tag{3}$$

c) Between importing tie lines and local demands

$$TD_{ij}^m = \frac{P_{gti}^m P_{dj}^m}{P_d^m}, \qquad \forall i \in BB^m, j \in B^m. \tag{4}$$

d) Between importing and exporting tie lines (wheeling exchanges)

$$TT_{ij}^m = \frac{P_{gti}^m P_{dtj}^m}{P_d^m}, \qquad \forall i, j \in BB^m. \tag{5}$$

Next, the use of each local line is defined as the sum of the uses of the line over all four types of exchanges and all possible bus pairs. Recall from [1] that according to the EBE approach, the use of line k by an equivalent bilateral exchange between buses i and j is defined by the product of the absolute value of the corresponding power transfer distribution factor (PTDF) [8], γ_{ijk}^m, and the power exchange itself, e.g., $|\gamma_{ijk}^m| GD_{ij}^m$. This is because any flow component due to an EBE $\gamma_{ijk}^m GD_{ij}^m$ is deemed to use the line, irrespective of its direction relative to the net line flow P_{fk}^m—in other words, that flows and counterflows are charged for line use indistinguishably. This property is crucial for the stability of rates of use by loads and generators, particularly if some line flows are near zero and can change direction following a small change in the operating conditions.

We recognize that our proposed equal treatment of flows and counterflows, both being assigned a line-use debit, may be contentious in systems where counterflows are deemed to help reduce the use of a line and are, therefore, assigned a line-use credit rather than a debit. We argue, however, that this distinction between flows and counterflows has a more solid justification when dealing with transmission-loss allocation, where the net flow is crucial in defining the line losses. In transmission-use allocation, however, even in a line with zero flow where counterflows and flows cancel out, the generating and consuming agents must be assigned some transmission use cost for this line.

The combined use of line k in area m by all four types of equivalent bilateral exchanges, therefore, is

$$\begin{aligned} U_k^m = &\sum_{i,j \in B^m} \left|\gamma_{ijk}^m\right| GD_{ij}^m + \sum_{i \in BB^m, j \in B^m} \left|\gamma_{ijk}^m\right| TD_{ij}^m \\ &+ \sum_{i \in B^m, j \in BB^m} \left|\gamma_{ijk}^m\right| GT_{ij}^m + \sum_{i,j \in BB^m} \left|\gamma_{ijk}^m\right| TT_{ij}^m. \end{aligned} \tag{6}$$

According to the EBE approach, the fraction of the known cost or regulated revenue of a line C_k assigned to an individual exchange is in proportion to the use of the line by the exchange relative to the combined use of the line by all exchanges. Therefore, the charge for the use of line k allocated to the exchange CGD_{ij}^m, denoted by CGD_{ijk}^m, is then

$$CGD_{ijk}^m = \left(\frac{C_k^m}{U_k^m}\right) \left|\gamma_{ijk}^m\right| GD_{ij}^m, \quad i \in B^m, j \in B^m, k \in L^m. \tag{7}$$

Similarly, the charge to exchange GT_{ij} for the use of line k is

$$CGT_{ijk}^m = \left(\frac{C_k^m}{U_k^m}\right) \left|\gamma_{ijk}^m\right| GT_{ij}^m, \ i \in B^m, j \in BB^m, k \in L^m. \tag{8}$$

The charge to exchange TD_{ij} is

$$CTD_{ijk}^m = \left(\frac{C_k^m}{U_k^m}\right) \left|\gamma_{ijk}^m\right| TD_{ij}^m, \ i \in BB^m, j \in B^m, k \in L^m. \tag{9}$$

Finally, the charge to exchange TT_{ij} becomes

$$CTT_{ijk}^m = \left(\frac{C_k^m}{U_k^m}\right) \left|\gamma_{ijk}^m\right| TT_{ij}^m, i \in BB^m, j \in BB^m, k \in L^m. \tag{10}$$

These basic charges are combined and distributed among the area generators, loads, and equivalent tie lines as follows: 1) The combined charge for the use of all lines in area m by an equivalent exchange between an internal generator i and an internal load j, $\sum_{k \in L^m} CGD_{ijk}^m$ is allocated in a 50/50 split between the generator and the load; 2) the charge for the use of all lines in area m by an exchange between a net import at bus i and an internal load j, $\sum_{k \in L^m} CTD_{ijk}^m$ is appended in full to the importing tie line. In a symmetric fashion, the cost for the use of all lines in area m by an exchange between an internal generation at bus i and a net export at bus j, $\sum_{k \in L^m} CGT_{ijk}^m$ is appended to the exporting tie line. Finally, the cost for the use of all lines in area m by a wheeling exchange between a net import at bus i and a net export at bus j, $\sum_{k \in L^m} CTT_{ijk}^m$ is divided in equal parts, with one half appended to the importing tie line and the other half assigned to the exporting tie line.

Then, the partial charges due to local network use allocated to generator i and to demand j in area m, denoted, respectively, by CG_i^m and CD_j^m, are given by

$$CG_i^m = \sum_{k \in L^m} \sum_{j \in B^m} \frac{CGD_{ijk}^m}{2}, \qquad i \in B^m \tag{11}$$

$$CD_j^m = \sum_{k \in L^m} \sum_{i \in B^m} \frac{CGD_{ijk}^m}{2}, \qquad j \in B^m. \tag{12}$$

The sum of the charges to all generators in area m for local EBEs is denoted by CG^m, while the corresponding total charges for the loads are denoted by CD^m.

2) Calculation of Tie-Line Augmented Costs: Since an equivalent tie line imports from one area and exports into another, let tie-line l export from area m and import into area n. The appended cost is then

$$\begin{aligned} CT_l^{\text{app}} = &\sum_{k\in L^m}\left\{\sum_{\substack{i\in B^m\\ j=j(l)}} CGT_{ijk}^m + \sum_{\substack{i\in BB^m\\ j=j(l)}} \frac{CTT_{ijk}^m}{2}\right\}\frac{P_{fl}}{P_{dtj}} \\ &+ \sum_{k\in L^n}\left\{\sum_{\substack{i=i(l)\\ j\in B^n}} CTD_{ijk}^n + \sum_{\substack{i=i(l)\\ j\in BB^n}} \frac{CTT_{ijk}^n}{2}\right\}\frac{P_{fl}}{P_{dtj}}; \\ &l\in ETL^m,\ l\in ITL^n. \end{aligned} \tag{13}$$

The symbols $j(l)$ and $i(l)$ in (13) show the boundary buses in areas m and n, respectively, to which tie-line l is connected. The sets of equivalent tie lines, respectively, exporting from area m and importing into area n are given by ETL^m and ITL^n.

The regional operators report the above-appended costs for each tie line to the IO, who then calculates the corresponding tie-line augmented costs by adding the appended costs to the original regulated tie-line costs CT_l^{reg}

$$CT_l^{\text{aug}} = CT_l^{\text{reg}} + CT_l^{\text{app}}. \tag{14}$$

3) Allocation of Augmented Tie-Lines Costs: The allocation of the augmented tie-line costs among the areas and the reconciliation of all charges and revenues are carried out through the following steps.

a) The IO determines the interarea EBEs, GD_{mn}. These area-wide EBEs or AEBEs represent equivalent exchanges between the total generation in area m, P_g^m, and the total demand in area n, P_d^n

$$GD_{mn} = \frac{P_g^m P_d^n}{P_d} \tag{15}$$

where $P_d = \sum_{q=1}^{na} P_d^q$ is the total demand of the interconnected system.

b) The IO now calculates the use of the tie lines by the area EBEs defined in step a). A fundamental assumption of this multiarea network cost allocation method is that the IO does not have access to detailed regional network information. Thus, to calculate the use of the tie lines by the area EBEs, an equivalent network model is used under which each area is represented by a single node with an equivalent single generator and load equal to the total area generation and demand, respectively. The equivalent tie-line reactances are modified to ensure that the power flows in the equivalent tie-line network remain the same as those in the original network and that the equivalent reactances are as close as possible to their original values. This can be done via a simple constrained optimization step. The IO now calculates the interarea tie-line power distribution factors γ_{mnl}^A, denoting the sensitivity of the power flow in tie-line l due to an injection into node area m and a corresponding extraction from node area n [1].

According to the EBE principle, the total use of tie-line l by all interarea equivalent exchanges GD_{mn}, therefore, is

$$UT_l = \sum_{m,n}\left|\gamma_{mnl}^A\right| GD_{mn}. \tag{16}$$

We emphasize that the calculation of tie-line use as defined in (16) includes interarea counterflows, which is an important characteristic to contain spatial and temporal volatility of the tie-line use charges [1].

c) The charge allocated to the interarea exchange GD_{mn} for the use of tie-line l is then

$$CGD_{mnl} = \left(\frac{CT_l^{\text{aug}}}{UT_l}\right)\left|\gamma_{mnl}^A\right| GD_{mn} \tag{17}$$

where CT_l^{aug} now represents the sum of the augmented costs of all tie-lines linking areas *m* and *n*.

d) From c), the IO calculates the tie-line use costs allocated to the total generation and demand in each area. For area m, these extra charges, denoted by ΔCG^m and ΔCD^m, are

$$\Delta CG^m = \sum_n\sum_l \frac{CGD_{mnl}}{2} \tag{18}$$

$$\Delta CD^m = \sum_n\sum_l \frac{CGD_{mnl}}{2}. \tag{19}$$

4) Final Allocation Among All Generators and Loads: The extra charges defined in (18) and (19) for the use of external networks are paid to the IO by the regional operators who collect them from the local generators and loads in a *pro rata* manner. These charges plus the flow-based charges already imposed for local-area use of (11) and (12) define the final allocation to all generators and loads in a region.

5) Refunds and Revenue Reconciliation: Since portions of the regional network-use costs due to exports, imports, and wheeling were passed on to the tie lines in the form of appended costs, the IO must now refund each area accordingly. Each regional operator, therefore, receives three types of refunds from the IO—one for exports, one for imports, and another for wheeling—that, along with the local use charges, are used to pay the local transmission provider.

The refund received by area m from the IO for exports to other areas is given by

$$RGT^m = \sum_{i,s,k} CGT_{ij(s)k}^m, \quad i\in B^m, s\in ETL^m, k\in L^m. \tag{20}$$

The refund from the IO for imports is

$$RTD^m = \sum_{r,j,k} CTD_{i(r)jk}^m, \quad r\in ITL^m, j\in B^m, k\in L^m. \tag{21}$$

Finally, the refund for wheeling exchanges is

$$RTT^m = \sum_{r,s,k} CTT_{i(r)j(s)k}^m, \ r\in ITL^m, s\in ETL^m, k\in L^m. \tag{22}$$

Clearly, the cost of regional network m, C^m must be equal to the amount already charged to its generators and loads for local use, plus the sum of the refunds from the IO for use of the area by imports, exports, and wheeling exchanges, i.e.,

$$C^m = CG^m + CD^m + RGT^m + RTD^m + RTT^m. \quad (23)$$

A second reconciliation relation requires that the total charges collected by the IO from the regions for tie-line use minus the total refunds paid by the IO to the regions must equal the sum of the regulated tie-line costs

$$\sum_l CT_l = \sum_m (\Delta CG^m + \Delta CD^m) - \sum_m (RGT^m + RTD^m + RTT^m). \quad (24)$$

Fig. 2 depicts the flows of funds among the regional operators, the IO, as well as the area and tie-line transmission owners.

III. Illustrative Examples

The proposed multiarea TCA approach (MAD) is first illustrated on the three-area, five-line, and six-bus network shown in Fig. 3.

The transmission use cost of each local line (L1, L2, and L3) is \$300/h, whereas that of each tie line (TL1 and TL2) is \$100/h. These costs include regulator-approved capital and operating costs. This test network illustrates the situation in a multiarea network where one area whose power is almost balanced (Area 2) is sandwiched between two large exporting (Area 1) and importing (Area 3) areas. This is similar to the situation between France, Switzerland, and Italy, where generators in France use the Swiss network to wheel power to the mostly importing Italian power system. This example has already been used in [2]. We recognize that the flows, loads, and generation levels used in this example do not represent the true French, Swiss, and Italian systems and have been exaggerated in order to illustrate the method.

The four main steps of the scheme MAD are now described in relation to this example.

1) *Allocation of local network costs*

Table I summarizes all of the regional EBEs as defined in (1)–(5), together with the corresponding charges for the use of the local area networks as defined by (7)–(10). Table I also shows in the last column the power transfer distribution factors (PTDFs or γ's) between the EBE and the local transmission line. Note that exchanges at the same bus have zero PTDFs, while all others are either 1 or -1 since each region in this example has only a single line.

As an example of how the EBE and charges shown in column five of Table I are calculated, consider the following EBE: $GD^1_{12} = P^1_{g1}P^1_{d2}/P^1_d = (108)(20)/108 = 20$ MW. The only element of the network used by this EBE is line L1 in area 1, with a cost of \$300/h. The only other use of this line is by the following EBE: $GT^1_{12} = P^1_{g1}P^1_{dt2}/P^1_d = (108)(88)/108 = 88$ MW. As for this simple case, the PTDFs for the EBEs are 1, the combined use of L1 by both EBEs is 108 MW. Thus, the charge allocated to the EBE GD^1_{12} is $(20/108)300 = 55.56$ \$/h, while the charge allocated to GT^1_{12} is $(88/108)300 = 244.44$ \$/h.

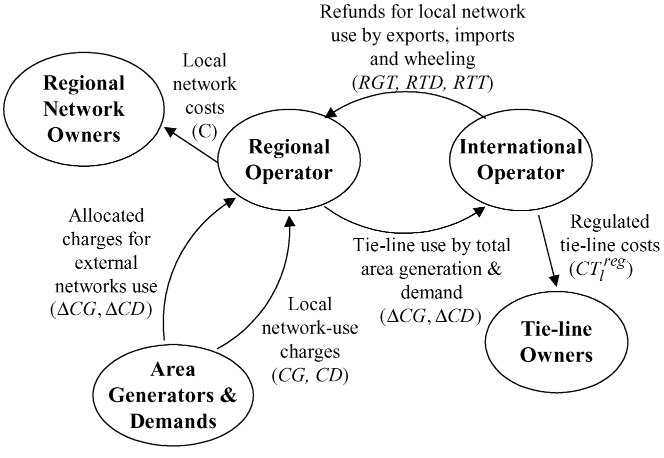

Fig. 2. Flow of funds between the IO, regional operators, and agents.

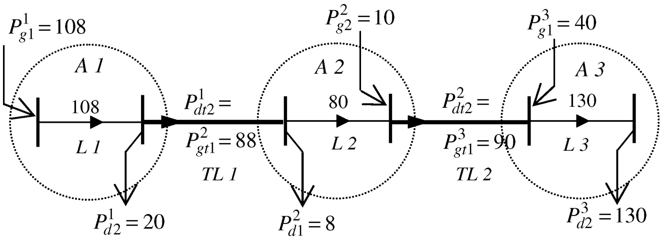

Fig. 3. Three-area test power system.

TABLE I
EBEs and Charges

Area	EBE Between:	Definition	EBE Amount (MW)	Charge to EBE (\$/h)	PTDF
1	Local G and D	$P^1_{g1}P^1_{d2} / P^1_d$	20.00	55.56	1
	Local G and tie-line to area 2	$P^1_{g1}P^1_{dt1} / P^1_d$	88.00	244.44	1
2	Local G and D	$P^2_{g2}P^2_{d1} / P^2_d$	0.82	3.00	-1
	Tie-line from area 1 and local D	$P^2_{gt1}P^2_{d1} / P^2_d$	7.18	0.00	0
	Tie-line from area 1 and tie-line to area 3	$P^2_{gt1}P^2_{dt2} / P^2_d$	**80.82**	**297.00**	1
	Local G and tie-line to area 3	$P^2_{g2}P^2_{dt2} / P^2_d$	9.18	0.00	0
3	Tie-line from area 2 and local D	$P^3_{gt1}P^3_{d2} / P^3_d$	90.00	207.69	1
	Local G and D	$P^3_{g1}P^3_{d2} / P^3_d$	40.00	92.31	1
			900.00		

TABLE II
AEBEs (MW) AND CORRESPONDING CHARGES ($/h)

			Demand		
			A 1	A 2	A 3
Gen	A 1	AEBE	13.67	5.47	88.86
		Charge	*0.00*	*26.78*	*824.29*
	A 2	AEBE	1.27	0.51	8.23
		Charge	*6.20*	*0.00*	*36.03*
	A 3	AEBE	5.06	2.03	32.91
		Charge	*46.97*	*8.87*	*0.00*

From the EBEs calculated in Table I, each region allocates their internal network costs among their own generators and demands as well as among their interconnecting tie lines. This is done following the rules defined by (7)–(12) and by the accompanying explanatory paragraphs. Recall that the regional charges to EBEs involving generations and loads are divided evenly among both parties and that the charges to EBEs involving tie lines (underlined in Table I) are allocated in full to the tie lines. For those EBEs involving only tie lines (shown in bold in Table I), the charges are allocated to the importing and exporting tie lines in a 50/50 split. For example, of the $55.56/h charged to GD_{12}^1, half ($27.78/h) is allocated to generator at bus 1 in area 1 and the other half to the load at bus 2 in area 1. Of the $244.44/h charged to GT_{12}^1, the full amount is allocated to the exporting tie-line TL1.

2) *Calculation of augmented tie-line costs*:

   All regions now report to the IO the fraction of the local use charges passed on to the tie lines, i.e., to the inter-regional network. At this stage, the IO first calculates the augmented tie-line costs by adding the regionally assigned costs to the original tie-line costs. In the example of Table I, the augmented tie-line cost for TL1 becomes $100 + 244.44 + 297/2 = 492.94$ \$/h, while that of TL2 becomes $100 + 207.69 + 297/2 = 456.19$ \$/h.

3) *Allocation of augmented tie-line costs*:

   The augmented tie-line costs are now distributed by the IO among the interarea EBEs (named AEBEs) according to (17). This intermediate result is shown in Table II.

   As an example of how the AEBEs and their charges are calculated in Table II, consider the AEBE between the total generation in area 1 (108 MW) and the total demand in area 2 (8 MW). This AEBE is given by $(108)(8)/158 = 5.47$ MW, where the total network demand is 158 MW. This AEBE only uses the tie line between area 1 and area 2, TL1, whose augmented cost as calculated above is $492.94/h. The interarea PTDF for this AEBE is 1. Since the total use of this tie line by all AEBEs is 100.66 MW (found by adding all AEBEs in Table II using TL1, that is, $100.66 = 5.47 + 88.86 + 1.27 + 5.06$), the charge allocated to this AEBE is $(5.47/100.66)(492.94) = 26.78$ \$/h, as shown in Table II.

   The IO then allocates the AEBE charges according to (18) and (19) to the area generation and load of each region. As an example, consider the area 1 generation, which has two AEBEs, one with the area 2 demand and another with the area 3 demand (the AEBE between the area 1 generation and demand does not use the tie-line network). This generator is responsible for half of the charges allocated to the two AEBEs between area 1 and areas 2 and 3, which from Table II, amounts to 26.78/2 and 824.29/2, respectively, for a total of $425.54/h.

TABLE III
FINAL LOCAL AND EXTERNAL CHARGES TO GENERATORS AND DEMANDS

		Local EBE's	External EBE's	Total
A 1	Generator	27.78	425.54	453.31
	Demand	27.78	26.58	54.36
A 2	Generator	1.50	21.11	22.61
	Demand	1.50	17.82	19.32
A 3	Generator	46.15	27.92	74.07
	Demand	46.15	430.16	476.31
Totals		*150.86*	*949.14*	*1100.00*

4) *Final allocation among all generators and loads*:

   In this step, the charges computed in the previous step for the use of the inter-regional network are collected by the regions from the area loads and generators in a *pro rata* manner and paid to the IO. These charges levied from the area loads and generators are in addition to the ones imposed in step 1 for EBEs involving local generation and demand only. For example, the final charge to the generator at bus 1 of area 1 is half of the charge allocated to GD_{12}^1, that is, $55.56/2 = 27.78$ \$/h, plus the $425.54/h found in step 3 for a total charge of $453.31/h.

   Table III presents the final total charges in dollars per hour to all generators and demands under the MAD approach. Note that the internal and external charges add up to the total cost of the internal area networks and the tie lines, that is, $1100/h. However, the total charges collected from the local EBEs do not add up to the cost of the area networks ($900/h). This is because the EBEs involving exports, imports, and wheeling account for a large part of the use of the network.

5) *Refunds and revenue reconciliation*:

   From Table III, we see that the IO collects a total of $949.14/h from all regions for the use of the tie-line network. After refunding the regions for the use of all local networks by all imports, exports, and wheeling shown in Table II underlined or bold $(244.44 + 297 + 207.69 = 749.14$ \$/h$)$, the IO has just enough funds to pay for the tie-line network ($200/h).

   As a further example of revenue reconciliation, consider area 2. The cost of this area ($300/h) according to (23) is collected in three parts: the charge assigned to the generator at bus 2 for local area use ($1.5/h), the charge assigned to the load at bus 1 for local area use ($1.5/h), and the refund from the IO for wheeling through this region ($297/h).

Referring to Table IV, columns 2 and 3 summarize the total charges to the generators and demands after allocating the AEBE costs to the already allocated local use costs. Columns 5 and 6 show the percent charges allocated relative to the cost of the local network (relative payments).

TABLE IV
FINAL ABSOLUTE AND RELATIVE PAYMENTS BY AREA

	CG^m (\$/h)	CD^m (\$/h)	Total (\$/h)	CG^m/C^m (%)	CD^m/C^m (%)	Total (%)
A 1	453.3	54.4	507.7	151.1	18.1	169.2
A 2	22.6	19.3	41.9	7.5	6.4	14.0
A 3	74.1	476.3	550.4	24.7	158.8	183.5
Total	550.0	550.0	1100	183.3	183.3	366.7

TABLE V
FINAL REGIONAL TRANSMISSION-USE RATES FOR GENERATION AND DEMAND

	P_g (MW)	CG^m/P_g (\$/MWh)	P_d (MW)	CD^m/P_d (\$/MWh)
A 1	108	4.20	20	2.72
A 2	10	2.26	8	2.42
A 3	40	1.85	130	3.66

Table V shows the transmission-use rates charged to the area generators and demands. Again, we observe that the generators in France and the loads in Italy face higher rates of use, that is, \$4.20/MWh and \$3.66/MWh, respectively. Note that the loads in France and the generators in Italy are subject to relatively low but nonzero rates of use, respectively, \$2.72/MWh and \$1.85/MWh. This is due to the fact that the MAD scheme allows counterflows even within the interarea allocation step. Had we used a method that does not allow counterflows, the loads in France and the generators in Italy would have paid zero amounts.

1) Observations on the Results of MAD in the Three-Region Case Study: 1) The full cost of the network, including tie lines (\$1100/h), has been fully allocated; 2) Switzerland (area 2) pays relatively little for the use of the entire network (\$41.9/h), which corresponds to 14% of its local network cost of \$300/h, with the remaining 86% being covered by the other areas. This is consistent with the fact that as Switzerland is used primarily for wheeling, the importing and exporting areas pay most of the Swiss area costs; 3) France and Italy not only pay enough to cover the costs of their local areas (\$507.7/MWh and \$550.4/h, respectively) but also for the costs of all tie lines and, as indicated above, for a large portion of the Swiss network; 4) Italy pays more than France since, other than the 40 MW of local generation, the Italian load of 130 MW is supplied by imports of 90 MW (88 MW from France and 2 MW from Switzerland); 5) the total percent allocation to the three areas adds up to 366.7% since the three areas constitute 300% or \$900/h, while the tie lines make up 66.7% of the cost of one of the areas or \$200/h.

We recognize that this illustrative example exaggerates the reality of the French–Swiss–Italian system. Since in this example the Swiss system has only a single line that is used almost exclusively for wheeling, it is normal that the neighboring systems are allocated most of the cost of this line. In a more realistic case study, the sandwiched system would have a larger proportion of local load and generation as well as many internal lines whose cost of use would be larger than the wheeling tie-line cost and that would be largely assigned to the local users.

The MAD methodology is further tested on a four-area, 72-bus system, based on the IEEE RTS network [6] whose topology is shown in Fig. 4. The costs of individual transmission lines are determined assuming typical line costs considering line length, voltage level, and capacity. The total transmission network costs of areas 1 and 4 are \$25 789/h each, while the network costs of areas 2 and 3 are \$10 360/h and \$11 984/h, respectively. The total cost of the 11 tie lines is \$9475/h, for a combined cost of the interconnected network of \$83 398/h.

Fig. 5 illustrates the reduced four-area interconnected network. The simulations carried out in this case study consider 8736 different hourly load conditions, as well as 8736 correspondingly different generation levels and transmission flows. The hourly, weekly, and seasonal demands follow the swings specified by the IEEE RTS system [7]. Fig. 5 shows one possible hourly state of the interconnected network of areas, corresponding to the annual average of the regional generation, load, and tie-line flows.

The MAD scheme and a single-area EBE transmission cost allocation (denoted by SA) is carried out on the four-area interconnected network for each of the 8736 annual hourly states. The SA allocation is in fact the first step in the MAX scheme and is used here as a benchmark against which to compare MAD. Table VI describes the time-average annual area rates for generators and loads in the four interconnected areas according to the MAD and SA schemes.

2) Observations on the Four-Region IEEE RTS Case Study:

a) From Table VI, we observe that the average annual rates under MAD and the benchmark single-area rates are not radically different, with the worst difference being less than 30%.
b) Areas 1 and 3, which from Fig. 5 are primarily exporting and importing, respectively, exhibit the largest differences between the MAD and SA rates.
c) For example, from Table VI, we see that the demands in area 1 pay \$8.81/MWh under MAD compared to \$6.77/MWh under SA, while the generators in this area pay \$7.80/MWh under MAD compared to \$8.63/MWh under SA. The SA rates are consistent with the general tendency of the EBE method to charge the loads in importing areas more than the generators and vice versa for exporting areas.
d) One possible explanation of the observation that the rates obtained under MAD do not follow closely the tendencies of the SA rates is that the decoupling process allocates part of the interconnected network costs in a *pro rata* manner.
e) Strict comparisons between the MAD and SA allocation results should be made with caution, tempered by the fact that the SA approach (and, therefore, the MAX scheme) is practically infeasible for very large continent-wide interconnected systems or where regions are autonomous and are not willing or able to exchange proprietary data.
f) There are other considerations that influence the results. For example, areas 1 and 4 have identical costs, but area 4 is "used" more extensively by wheeling and exports than area 1. Higher exports tend to increase the generator rates since they make greater use of external

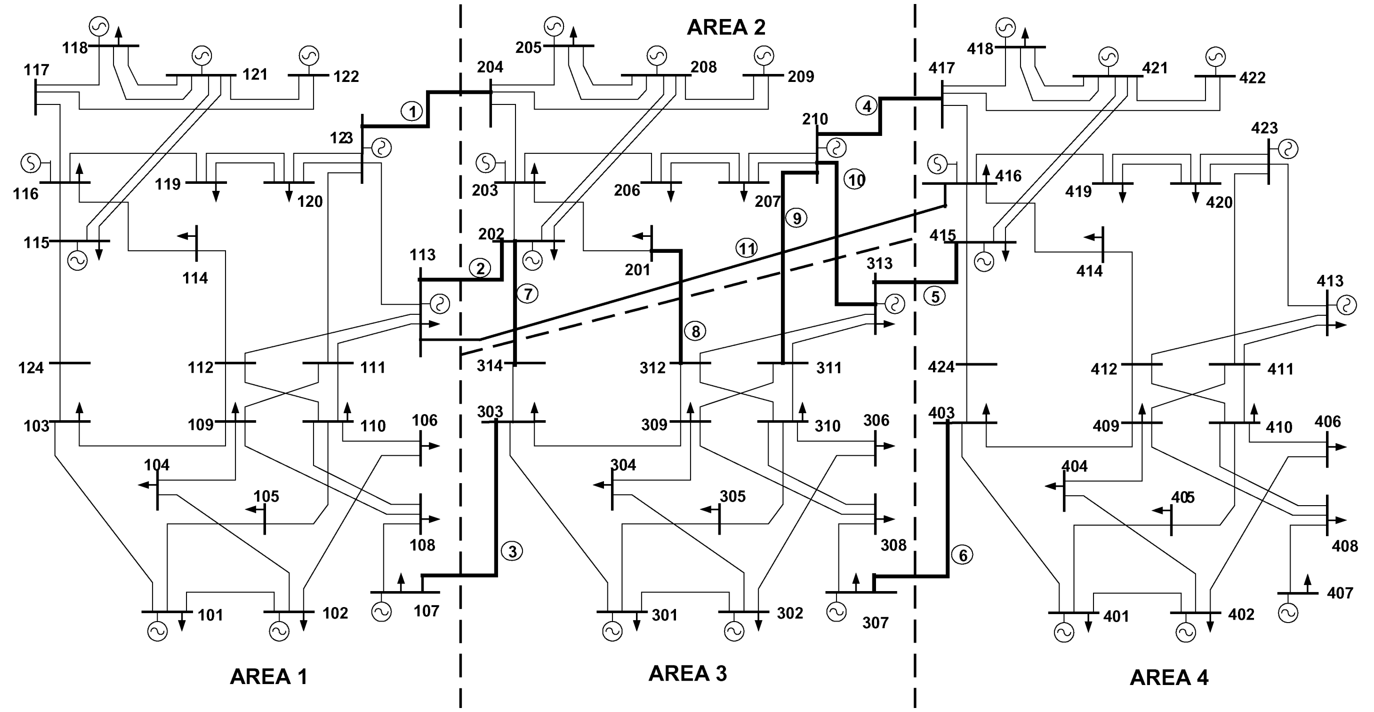

Fig. 4. Four-area 72-bus test power system.

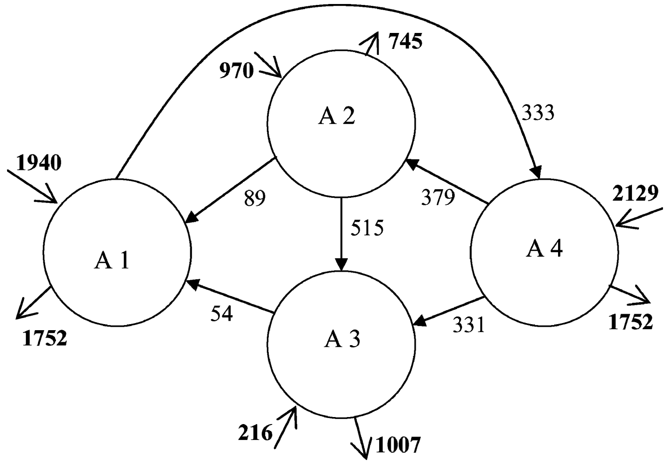

Fig. 5. Average annual area generations, demands, and interarea flows (MW).

TABLE VI
AVERAGE ANNUAL AREA TRANSMISSION-USE RATES IN DOLLARS PER MEGAWATTHOUR

	Area Demand		Area Generation	
	MAD	SA	MAD	SA
A 1	8.81	6.77	7.80	8.63
A 2	7.06	6.09	7.05	7.61
A 3	7.05	9.43	7.96	7.71
A 4	8.68	9.02	8.47	7.39

networks, while higher wheeling in a region tends to reduce local load and generator payments since external agents are making greater use of the local network. The average rates under MAD paid by generators in area 4 (primarily exporting) are higher than the average rates paid by generators in area 1, which although exporting, it is less so. The average rates paid by loads in areas 1 and 4 are about the same, perhaps because of the above-mentioned wheeling effect in area 4.

IV. CONCLUSION

We have examined the TCA problem for very large networks with multiple interconnected regions or countries. A recent proposal, called MAX, calls for a single-area TCA algorithm to be executed on the full inter-regional network, the result of which is then used to calculate aggregated inter-regional compensations. Under MAX, each region receives a bill for its share of the use of every other region. Likewise, each region receives a bill for its share of the use of the inter-regional network of tie lines.

The main concern about the MAX scheme is that its implementation requires a centralized entity, here called the IO, to have access to detailed network and load flow data across regions or countries that typically are autonomous and may not be willing or able to share this data. In addition, the MAX scheme must first calculate detailed inter-regional and local transmission-use charges only to aggregate them into lumped inter-regional payments. The result is that the original flow-based allocation signals are filtered out and lost, replaced by inter-regional postage stamp charges.

These concerns led to the development and testing of a new multiarea TCA scheme named MAD. In this decoupled approach, each region carries out its own TCA following its chosen rules. In addition, in order to calculate the use of the tie-line network by the regional generators and loads, the IO does not require detailed information about regional networks, relying only on the characteristics of the tie-line network.

This is a key issue, especially in North America, considering FERC's intention to provide RTOs with exclusive autonomy to provide transmission service and to set and administer local transmission-use tariffs.

It may also be noted that the notion of pancaking does not apply to MAD, since pancaking is used for bilateral contracts based on predefined paths. Under MAD, all generation levels and loads, whether defined by a pool market-clearing scheme or by an operator-approved bilateral agreement, are subject to the same transmission cost allocation rules.

Finally, although MAD is general enough to allow each region to define its particular cost allocation rules, if all regions agreed, a continent-wide common set of rules could be put in place.

Simulations were made on a simple three-area system and on the four-area version of the IEEE RTS 96 system for hourly load and generation conditions over a one-year period. The first case illustrates in great detail the various steps of the MAD scheme combined with the EBE principle. The results for the larger four-area case study show that under MAD, the average rates paid by areas are consistent with the rates obtained using a benchmark TCA single-area scheme based on the EBE principle.

APPENDIX
PRINCIPLE OF EQUIVALENT BILATERAL EXCHANGES

The EBE principle [1] states that each demand is supplied by a fraction of each generator uniformly divided among all generators. Analogously, each generator supplies a fraction of each demand uniformly divided among all demands. In a single area system, an EBE between a generation P_{gi} at bus i and a demand P_{dj} at bus j by is given by $GD_{ij} = P_{gi}P_{dj}/P_d^{sys}$, where the system demand is given by $P_d^{sys} = \sum_j P_{dj} = \sum_i P_{gi}$.

Letting γ_{ijk} be the well-known power transfer distribution factor [8], the flow in line k can be expressed as $P_{fk} = \sum_{i,j} \gamma_{ijk} GD_{ij}$. If the "use" of line k by GD_{ij} is $U_{ijk} = |\gamma_{ijk}| GD_{ij}$, then the use of the line by generation P_{gi} is $UG_{ik} = \sum_j |\gamma_{ijk}| GD_{ij}$, while the use by demand P_{dj} is $UD_{jk} = \sum_i |\gamma_{ijk}| GD_{ij}$. Also, defining the use of line k by all EBEs as $UL_k = \sum_{i,j} |\gamma_{ijk}| GD_{ij}$, the rate of use of line k with cost C_k becomes $r_k = C_k/UL_k$. The total charge allocated to generation P_{gi} is then $CG_i = \sum_k r_k UG_{ik}/2$, while the total charge to demand P_{dj} is $CD_j = \sum_k r_k UD_{jk}/2$.

One important feature of the EBE method is that it is not dependent on the arbitrary choice of a slack bus since the receiving bus of each EBE acts as its own slack.

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