A Congestion–Management Allocation Mechanism for Multiple Transaction Networks

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***Abstract*—In this paper, we present a physical-flow-based congestion management allocation mechanism for multiple transaction networks. We use the multiple transaction network framework constructed in [1] to characterize transmission congestion and then determine the contribution to congestion attributable to each transaction on a physical-flow basis. This allocation scheme explicitly addresses the issue of counter flows. The allocation results are used in the congestion relief of the independent grid operator (IGO) so as to allow it to acquire relief services to remove the overload congestion attributed to each transaction from the network in the most economic manner. The congestion charges attributable to each transaction for its usage of the network are also determined. We tested the proposed scheme on several systems and we illustrate its capabilities on a network based on the IEEE 57-bus system. We discuss the policy implications of the congestion relief allocation solution. The proposed scheme provides physically reasonable results and is applicable to large-scale networks.**

***Index Terms*—Allocation mechanisms, congestion management allocation, multiple transaction networks, open access transmission regimes, transmission pricing.**

I. Introduction

THE OPEN access transmission regime plays a central role in the rapid disintegration of the well-entrenched vertically integrated structure of the electric industry. This regime has resulted in the entry of a large number of new players and the proliferation in the number of transactions. In the new competitive electricity market environment, the transmission system takes on a *common carrier* role. These changes are bringing about the establishment of an independent grid operator (IGO) such as the various independent system operator and regional transmission organization (RTO) entities in existence or under formation. One of the IGO's key functions is congestion management [2].

Congestion occurs whenever the transmission network is unable to accommodate all the desired transactions due to the violation of one or more constraints for the resulting state under both the base case and a set of specified contingencies. The open access transmission regime results in the more intensive use of the transmission system, which, in turn, leads to more frequent congestion. The task of congestion management requires the IGO to identify and relieve such situations through the deployment of various physical or financial mechanisms. Since the scope of these congestion management activities includes the determination of the actual transmission usage by the individual transactions, the IGO has significant financial impacts on each market participant. A basic requirement is that the congestion management and pricing be nondiscriminatory and transparent.

For different power market structures, the approaches to managing congestion may vary. Various congestion management schemes for the different restructuring paradigms have appeared in the literature. Hogan proposed the contract network and nodal pricing approach [3] using the spot pricing theory [4] for the so-called *Poolco* paradigm. In the nodal pricing approach, congestion management is performed through a *centralized* optimal dispatch, while transmission charges are determined *ex post* and set to the nodal spot price differences. Chao and Peck proposed in [5] an alternative which is based on parallel markets for link-based transmission capacity rights and energy trading under a set of rules defined and administrated by the IGO. These rules specify the transmission capacity rights required to support any bilateral transactions and are adjusted continuously to reflect changing system conditions. In the so-called *coordinated multilateral trade* framework developed by Wu and Varaiya [6], economic decisions are carried out through multilateral trades and the reliability function is coordinated by the IGO who provides publicly accessible data for generators and consumers to use in determining feasible and profitable trades. An attractive property of the formulation is that any sequence of such coordinated private multilateral trades leads to efficient operations maximizing social welfare. The two schemes [5], [6] have in common the reliance on decentralized decision making and market forces. However, their implementation would require the availability of a highly sophisticated market and advanced information technology.

Several optimal power flow (OPF)-based congestion management schemes for multiple transaction systems have been proposed. An approach to relieving congestion using the minimum total modification to the desired transactions was presented in [7]. A variant of this least modification approach [8] used a weighting scheme with the weights being the surcharges paid by the transactions for transmission usage in the congestion-relieved network. The congestion management scheme for the California independent grid operator (ISO) [9] aims to relieve the network of interzonal congestion using the adjustment offers of the scheduling coordinators. In this paper, a scheduling coordinator and a transaction are conceptually synonymous entities. The congestion relief objective is to maximize the value of the limited transfer capability measured by the offers. Every

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entity scheduling flow on a congested path is charged the transmission usage charge for its flow on the congested line. Transmission usage charges are specified by the shadow price of the problem formulation. An important feature of this scheme is the enforcement of the *separation of markets* constraint to ensure that the IGO does not create new transactions that the scheduling coordinators did not initiate on their own. A similar adjustment-auction-based scheme [10] differs from that of [9] in that the *separation of the markets* constraint on each scheduling coordinator is not introduced.

The key contribution of this paper is the development of a *new* mechanism for the allocation of congestion management in multiple transaction networks on a physical flow basis. While there is a growing body of congestion management literature, the critical issue of congestion allocation on a physical-flow basis has not been addressed so far. This paper presents a physical-flow-based mechanism in which congestion is appropriately allocated among the transactions on the system. The proposed allocation scheme enables the IGO to acquire the congestion relief services for each transaction to remove its congestion contribution at *least cost* and to determine the *nondiscriminatory* congestion charges for each transaction's network usage. The proposed mechanism explicitly considers the presence of counter flows and provides a physically more attractive basis than the approach that simply assigns the marginal-cost-based charges to each of the transactions on the network. The latter may result in overcollection and may not appropriately charge each transaction for the "burden" it causes. The proposed scheme is applicable to a transaction-based market structure in which the IGO is in charge of acquiring congestion relief services in the most economic manner.

This remainder of this paper is organized as follows. Section II focuses on the development of an allocation mechanism to determine the allocation attributed to each transaction of its contribution to the network congestion. Section III formulates the IGO's least-cost congestion relief problem. We present the optimality analysis and develop the transmission usage pricing scheme. Section IV is devoted to the presentation of numerical results and some discussion of the key policy implications of the proposed mechanism.

We focus on the congestion issue for the forward markets such as the next day or the next hour markets. In such cases the analysis is done on an hourly basis. Note that congestion may occur due to the onset of a contingency in the real-time operation of the power system. However, congestion due to contingencies is outside the scope of the paper. The long-term solution for congestion through transmission system expansion is also not addressed in this paper.

II. Congestion Allocation

We use the definition of a bilateral real power transaction and the multiple-transaction framework explicitly recasting the power flow problem in terms of all the transactions on the system that we developed in [1]. We consider a system of $N+1$ buses with the swing bus at bus 0 and the set $\mathcal{M}$ of transactions. A bilateral transaction $m \in \mathcal{M}$ is a set of selling buses (injection buses) $S^{(m)}$ supplying a specified amount of real power $t^{(m)}$ to a set of buying buses (withdrawal buses) $\mathcal{B}^{(m)}$

$$\mathcal{T}^{(m)} = \left\{ t^{(m)}, \mathcal{S}^{(m)}, \mathcal{B}^{(m)} \right\}. \tag{1}$$

In this triplet, the set $\mathcal{S}^{(m)}$ is the collection of 2-tuples

$$\mathcal{S}^{(m)} = \left\{ \left(s_i^{(m)}, \sigma_i^{(m)} \right), i = 1, 2, \ldots N_s^{(m)} \right\} \tag{2}$$

with the selling bus $s_i^{(m)}$ supplying $\sigma_i^{(m)} t^{(m)}$ MW of the transaction amount. The fractions $\sigma_i^{(m)}$ must satisfy the conditions $\sum_{i=1}^{N_s^{(m)}} \sigma_i^{(m)} = 1$ with $\sigma_i^{(m)} \in [0, 1]$, $i = 1, 2, \ldots N_s^{(m)}$, where $N_s^{(m)}$ is the number of selling buses in transaction m. Similarly, $\mathcal{B}^{(m)}$ is the collection of 2-tuples

$$\mathcal{B}^{(m)} = \left\{ \left(b_j^{(m)}, \beta_j^{(m)} \right), j = 1, 2, \ldots N_b^{(m)} \right\} \tag{3}$$

where the buying bus $b_j^{(m)}$ receives $\beta_j^{(m)} t^{(m)}$ MW of the transaction amount. The fraction $\beta_j^{(m)}$ must satisfy the conditions $\sum_{j=1}^{N_b^{(m)}} \beta_j^{(m)} = 1$ with $\beta_j^{(m)} \in [0, 1]$, $j = 1, 2, \ldots N_b^{(m)}$, where $N_b^{(m)}$ is the number of buying buses in transaction m. Note that this general framework allows any number of selling and/or buying entities at each network bus.

We characterize transmission congestion within this framework and then determine the contribution to congestion attributable to each transaction. We denote by $\mathcal{L}$ the set of transmission lines. We refer to the flows that result from these proposed transactions as the *preferred schedule* flows and denote by f_ℓ the real power flow in line $\ell \in \mathcal{L}$. We adopt the convention that $f_\ell \geq 0$ so that the flow from the *from* bus to the *to* bus is always nonnegative. We simplify the representation of the various transmission constraints and model them in terms of line flow limits: each line ℓ has the flow limit $f_\ell^{\max}$. In this model, congestion corresponds to the overloading of one or more transmission lines in the preferred schedule flows. Since congestion due to contingencies is not addressed in the paper, we only consider f_ℓ and $f_\ell^{\max}$ for the base case. (Conceptually, the proposed approach is extendable to contingency cases; the computational aspects require some additional efforts to make the scheme numerically efficient for large systems with many contingencies.) Let $\tilde{\mathcal{L}} \subset \mathcal{L}$ be the subset of overloaded lines, i.e.

$$\tilde{\mathcal{L}} \triangleq \{ \ell \in L : f_\ell > f_\ell^{\max} \} \tag{4}$$

and let Δf_l denote the overload in line $\ell \in \tilde{\mathcal{L}}$

$$\Delta f_\ell \triangleq f_\ell - f_\ell^{\max}. \tag{5}$$

Consider the overloaded line $\ell \in \tilde{\mathcal{L}}$. We represent Δf_ℓ in terms of the proposed transactions. Let line ℓ join buses i and j. We assume that the effects of the shunt elements on the real power line flow are negligible and so the line is represented by its line impedance $r_{ij} + jx_{ij}$. We define $g_{ij} \triangleq r_{ij}/(r_{ij}^2 + x_{ij}^2)$ and $b_{ij} \triangleq x_{ij}/(r_{ij}^2 + x_{ij}^2)$. The voltage magnitude V_n and angle θ_n for buses $n = 1, 2, \ldots, N$ are a function of $\mathcal{M}$ [1]. Then, the line flow f_ℓ from bus i to bus j is given by

$$f_\ell = g_{ij} \left[V_i^2 - V_i V_j \cos(\theta_i - \theta_j) \right] + b_{ij} \left[V_i V_j \sin(\theta_i - \theta_j) \right]. \tag{6}$$

Under the assumption that the dc power flow conditions hold, we may approximate f_ℓ by

$$\tilde{f}_\ell = [g_{ij}(\theta_i - \theta_j)/2 + b_{ij}]\,(\theta_i - \theta_j). \tag{7}$$

Next, we define $\underline{\hat{\theta}} = [\hat{\theta}_1, \hat{\theta}_2, \ldots, \hat{\theta}_N]^T$ as the voltage angle vector computed by the dc power flow. Without any loss of generality, we may set to zero the value of $\hat{\theta}_0$ at the slack bus. Then

$$\hat{\theta}_i - \hat{\theta}_j = \sum_{m \in \mathcal{M}} \pi_{ij}^{(m)} t^{(m)}, \qquad i, j = 0, 1, 2, \ldots, N, i \neq j \tag{8}$$

with the definition of $\pi_{ij}^{(m)}$ and the derivation of (8) given in Appendix A. In order to express the approximation of the line flow in terms of the proposed transactions, we further approximate $\tilde{f}_\ell$ in (7) by

$$\begin{aligned}\hat{f}_\ell &= [g_{ij}(\theta_i - \theta_j)/2 + b_{ij}]\,(\hat{\theta}_i - \hat{\theta}_j)\\ &= [g_{ij}(\theta_i - \theta_j)/2 + b_{ij}] \sum_{m \in \mathcal{M}} \pi_{ij}^{(m)} t^{(m)}\\ &= \sum_{m \in \mathcal{M}} \left\{[g_{ij}(\theta_i - \theta_j)/2 + b_{ij}]\,\pi_{ij}^{(m)}\right\} t^{(m)}. \end{aligned} \tag{9}$$

If we define for each $m \in \mathcal{M}$

$$\varphi_\ell^{(m)} \triangleq [g_{ij}(\theta_i - \theta_j)/2 + b_{ij}]\,\pi_{ij}^{(m)} \tag{10}$$

then[1]

$$\hat{f}_\ell = \sum_{m \in \mathcal{M}} \varphi_\ell^{(m)} t^{(m)}. \tag{11}$$

In (11), we may consider $\varphi_\ell^{(m)} t^{(m)}$ to be the flow attributable to transaction m in the preferred schedule with the sign of $\varphi_\ell^{(m)}$ indicating the direction of the contribution to the flow f_ℓ associated with transaction m. For each overloaded line ℓ, we partition $\mathcal{M}$ into two nonintersecting subsets $\mathcal{D}_\ell$ and $\mathcal{C}_\ell$

$$\mathcal{D}_l \triangleq \left\{m \in \mathcal{M}\colon \varphi_\ell^{(m)} \geq 0\right\}, \mathcal{C}_l \triangleq \left\{m \in \mathcal{M} : \varphi_\ell^{(m)} < 0\right\}. \tag{12}$$

Thus, $\mathcal{D}_\ell$ is the subset of the transactions whose associated flows are in the same direction as the net flow f_ℓ. We call such a flow a *dominant flow*. Conversely, $\mathcal{C}_\ell$ is the subset of transactions, if any, whose associated flows are in the opposite direction to f_ℓ. We call such a flow a *counter flow*. It follows from (5), (11), and (12) that the overload Δf_ℓ may be approximated by[2]

$$\begin{aligned}\Delta\tilde{f}_\ell &= \sum_{m \in \mathcal{M}} \varphi_\ell^{(m)} t^{(m)} - f_\ell^{\max}\\ &= \sum_{m \in \mathcal{D}_\ell} \varphi_\ell^{(m)} t^{(m)} - \left\{ f_\ell^{\max} + \left[- \sum_{m \in \mathcal{C}_\ell} \varphi_\ell^{(m)} t^{(m)} \right] \right\}. \end{aligned} \tag{13}$$

Since each transaction in $\mathcal{D}_l$ results in dominant flows on the overloaded line ℓ, these flows contribute to the overload in ℓ. On the other hand, each transaction in $\mathcal{C}_l$ results in counter flows and the flows, in effect, increase the line flow limit from $f_\ell^{\max}$ to $f_\ell^{\max} + [\sum_{m \in \mathcal{C}_\ell} -\varphi_\ell^{(m)} t^{(m)}]$. Therefore, the line ℓ overload is attributed in its entirety to the transactions in $\mathcal{D}_\ell$.

We define for each transaction $m \in \mathcal{M}$

$$\tilde{\mathcal{L}}^{(m)} \triangleq \left\{\ell\colon \ell \in \tilde{\mathcal{L}} \quad \text{and} \quad \varphi_\ell^{(m)} \geq 0\right\} \tag{14}$$

the subset of overloaded lines with the associated flows that contribute to the dominant flows in the lines. Note that for a given m, $\tilde{\mathcal{L}}^{(m)}$ may be empty. Let $\hat{\mathcal{M}} = \bigcup_{\ell \in \tilde{\mathcal{L}}} \mathcal{D}_\ell$. Then $\hat{\mathcal{M}} \subset \mathcal{M}$ is the subset of those transactions that contribute to the overloads in one or more lines. If, in addition, we assume that the line overload Δf_ℓ is contributed *uniformly* by each transaction in $\mathcal{D}_\ell$, then the contribution to Δf_ℓ attributable to transaction $m \in \mathcal{D}_\ell$ is

$$\Delta f_\ell^{(m)} = \frac{\varphi_\ell^{(m)} t^{(m)}}{\sum\limits_{m' \in \mathcal{D}_\ell} \varphi_\ell^{(m')} t^{(m')}}\,\Delta f_\ell \approx \frac{\varphi_\ell^{(m)} t^{(m)}}{\sum\limits_{m' \in \mathcal{D}_\ell} \varphi_\ell^{(m')} t^{(m')}}\,\Delta\tilde{f}_\ell. \tag{15}$$

We use the approximation in (15) as the basis for the congestion relief actions.

III. Congestion Relief

To determine the actions to remove congestion, we assume that the only congestion relief means available to the IGO are the acquisition of incremental/decremental injections into the system nodes from every willing participant, be it a generating or a load entity. To do so, the IGO runs an auction of incremental/decremental adjustments to select the most economic means to provide overload relief. We note that the participants in the adjustment auction need not be limited to be participants in the proposed transactions.

Let $\mathcal{K}$ be the set of buses where the auction participants are located. The bidder at bus k submits an offer with the \$/MW price for the net injection adjustment Δp_k. Note that while a generator may provide Δp_k by increasing or decreasing its production output, a load may also effectively offer Δp_k by varying its demand by $-\Delta p_k$. The incremental injection $\Delta p_k > 0$ (decremental injection $\Delta p_k < 0$) offer has a charge of c_k^+ \$/MW (a rebate of c_k^- \$/MW).[3] In its offer, the bidder also specifies the lower and upper limits within which it is physically capable and/or willing to provide its injection adjustment $\Delta p_k \in [\Delta p_k^{\min}, \Delta p_k^{\max}]$. If the IGO accepts the offer of the participant at bus k, then it pays $c_k^+ \Delta p$ for $\Delta p_k \geq 0$ to, or receives $-c_k^- \Delta p_k$ for $\Delta p_k < 0$ from, the bidder. The IGO uses the offers submitted by the generators and the loads to determine the most economic congestion relief by minimizing the total costs incurred.[4] The decision variables for the IGO are the relief actions $\Delta p_k^{(m)}$, $k \in \mathcal{K}$, $m \in \hat{\mathcal{M}}$. $\Delta p_k^{(m)}$ is the net incremental/decremental injection acquired from the bidder at

[1]Note that if we assume that $r_{ij} \ll x_{ij}$ and that $|\theta_i - \theta_j|$ is small, then $g_{ij}|\theta_i - \theta_j|/2 \ll b_{ij} \approx 1/x_{ij}$. Consequently, $\varphi_\ell^{(m)} \approx \pi_{ij}^{(m)}/x_{ij}$ so that the approximation in (11) is relatively straightforward to compute.

[2]Although the approximation makes use of some dc power flow assumptions for simplifying the ac power flow expression for f_ℓ, we do *not* use the dc power flow to model the transmission network. The simplified representation in (7)–(13) used to explicitly express the overflow Δf_ℓ in terms of all the transactions on the network. The expression in (13) provides a physical-flow basis for allocating the overload congestion to each transaction.

[3]We assume that the participants in the auction are rational bidders so that at bus k, $c_k^- \leq c_k^+$.

[4]While a uniform price auction is typically used in the forward energy markets, the adjustment auction for the transmission market is a pay-as-bid auction.

bus k for transaction m to relieve the overload burden $\Delta f_\ell^{(m)}$, $\ell \in \tilde{\mathcal{L}}^{(m)}$ attributed to the transaction m. The IGO's objective function is to

$$\min Z = \sum_{k \in \mathcal{K}} c_k \left[\sum_{m \in \hat{\mathcal{M}}} \Delta p_k^{(m)} \right] \tag{16}$$

where

$$c_k = \begin{cases} c_k^+ & \text{if } \Delta p_k = \sum_{m \in \hat{\mathcal{M}}} \Delta p_k^{(m)} \geq 0 \\ c_k^- & \text{otherwise.} \end{cases} \tag{17}$$

We use a small signal model to analyze the effects on the transmission network of $\Delta p_k^{(m)}$, $k \in \mathcal{K}$, $m \in \hat{\mathcal{M}}$. This is reasonable because $\Delta p_k^{(m)}$ are typically small changes in the net injections at the buses $k \in \mathcal{K}$ compared to the injection levels for the proposed transactions. We use the sensitivities $\partial f_\ell / \partial p_k$ of the line flow f_ℓ with respect to the net injection p_k at bus k to study the changes in the line flows in response to $\Delta p_k^{(m)}$. From the approximation $\tilde{f}_\ell$ of f_ℓ in (7), we obtain

$$\begin{aligned} \frac{\partial f_\ell}{\partial p_k} &\approx \frac{\partial \tilde{f}_\ell}{\partial p_k} = [g_{ij}(\theta_i - \theta_j) + b_{ij}] \left(\frac{\partial \theta_i}{\partial p_k} - \frac{\partial \theta_j}{\partial p_k} \right) \\ &\approx [g_{ij}(\theta_i - \theta_j) + b_{ij}] \left(\frac{\partial \hat{\theta}_i}{\partial p_k} - \frac{\partial \hat{\theta}_j}{\partial p_k} \right). \end{aligned} \tag{18}$$

It follows from (A8) in Appendix A that

$$\frac{\partial \hat{\theta}_i}{\partial p_k} - \frac{\partial \hat{\theta}_j}{\partial p_k} = d_{kj} - d_{ki}. \tag{19}$$

The definitions of d_{ij}, $i, j = 0, 1, 2, \ldots, N$ are the elements of $\underline{D} = [\underline{B}]^{-1}$ the inverse of the dc power flow matrix in [11]. We define

$$\psi_{\ell, k} \triangleq [g_{ij}(\theta_i - \theta_j) + b_{ij}](d_{kj} - d_{ki}). \tag{20}$$

Since $\psi_{\ell, k} \approx (\partial f_\ell / \partial p_k)$, $\psi_{\ell, k}$ provides the expression for the approximation to the rate of the change in the line flow f_ℓ with respect to the change in the net injection at bus k.

The constraints the IGO congestion relief actions need to satisfy are as follows.

i) *Power Balance*:

$$\sum_{k \in \mathcal{K}} \sum_{m \in \hat{\mathcal{M}}} \Delta p_k^{(m)} = 0. \tag{21}$$

ii) *Removal of Overloads*:

$$-\sum_{k \in \mathcal{K}} \psi_{\ell . k} \Delta p_k^{(m)} = \Delta f_\ell^{(m)}, \qquad \ell \in \tilde{\mathcal{L}}^{(m)}, m \in \hat{\mathcal{M}}. \tag{22}$$

iii) *No Overloads in the IGO Schedule*:

$$f_\ell + \sum_{k \in \mathcal{K}} \psi_{\ell, k} \Delta p_k \leq f_\ell^{\max}, \qquad \ell \in L. \tag{23}$$

iv) *Increment/Decrement Limits*:

$$\Delta p_k^{\min} \leq \Delta p_k^{(m)} \leq \Delta p_k^{\max}, \qquad k \in \mathcal{K}. \tag{24}$$

v) *Total Increment/Decrement Limits*:

$$\Delta p_k^{\min} \leq \Delta p_k \leq \Delta p_k^{\max}, \qquad k \in \mathcal{K}, m \in \hat{\mathcal{M}}. \tag{25}$$

vi) *Separation of Markets*:

$$\sum_{k \in \mathcal{S}^{(m)} \bigcup \mathcal{B}^{(m)}} \Delta p_k = 0, \qquad m \in \hat{\mathcal{M}}. \tag{26}$$

The equality constraints in (22) ensure that the congestion relief acquired by the IGO for each transaction $m \in \mathcal{D}_\ell$ is exactly the amount of overload $\Delta f_\ell^{(m)}$ attributable to that transaction. However, since the relief actions acquired for one overload may exacerbate another overload or even lead to a *new* overload, the inequality (23) is introduced to ensure that there is no overload violation after the congestion relief. The constraints in (26) are imposed to keep the generation and the load within each transaction balanced in the congestion relief so as to prevent the IGO from implicitly arranging new transactions among market participants.

The decision variables of the linear program (LP) $\Delta p_k^{(m)}$, $k \in \mathcal{K}$, $m \in \hat{\mathcal{M}}$ are determined for each entity k wishing to participate in the adjustment auction. Each such entity needs to specify only Δp_k. While not all the transacting parties in $\mathcal{M}$ necessarily participate in this adjustment auction, there may be also nontransacting parties in $\mathcal{K}$.

The formulation in (16)–(26) obtains an LP for the IGO's least-price congestion relief problem. This congestion management problem formulation is very general and includes the various formulations [9], [10] that previously appeared in the literature as special cases. In particular, without the equality constraints in (22), $\sum_{m \in \hat{\mathcal{M}}} \Delta p_k^{(m)}$ is replaced by Δp_k so that the formulation of the scheme in [9] results; in addition, without the separation of markets constraint in (26), the formulation becomes that in [10].

We next undertake the optimality analysis. We denote by $\Delta p_k^{*(m)}$ and Z^* the optimal solution and the corresponding congestion relief costs, respectively. We denote the values of the dual variables at the optimum associated with (22) and (23) by $\rho_l^{*(m)}$ and μ_l^*, respectively. Note that $\mu_\ell^* \geq 0$. We consider the sensitivity $\chi_\ell^* = -\partial Z^*(f_\ell^{\max}) / \partial f_\ell^{\max} = \partial Z^*(f_\ell) / \partial f_\ell$. We use the LP formulation to evaluate

$$\chi_\ell^* = \begin{cases} \mu_\ell^* + \sum_{m \in \mathcal{D}_\ell} \left[\dfrac{\rho_\ell^{*(m)} \varphi_\ell^{(m)} t^{(m)}}{\sum_{m' \in \mathcal{D}_\ell} \varphi_\ell^{(m')} t^{(m')}} \right] & \text{if } \ell \in \tilde{\mathcal{L}} \\ \mu_\ell^* & \text{otherwise.} \end{cases} \tag{27}$$

For $\ell \in \tilde{\mathcal{L}}$, one unit decrease in $f_\ell^{\max}$ results in an increase of $(\varphi_\ell^{(m)} t^{(m)} / \sum_{m' \in \mathcal{D}_\ell} \varphi_\ell^{(m')} t^{(m')})$ in the congestion burden associated with each transaction $m \in \mathcal{D}_\ell$. Thus, the first component of χ_ℓ^* in (27) is the sum of the additional congestion expenditures incurred by the IGO in relieving the increased congestion burdens. The expenditures μ_ℓ^* are incurred to ensure that there is no overload in the IGO-determined schedule. We may use χ_ℓ^* to set up the uniform transmission usage prices charged to each transaction for its flows on line ℓ in the IGO-determined schedules. Note, however, that χ_ℓ^* may be negative for some $\ell \in \tilde{\mathcal{L}}$.

The physical interpretation of a negative χ_ℓ^* is that a decrease in the flow limit $f_\ell^{\max}$ or equivalently an increase in the line flow f_ℓ in the preferred schedule is the optimal decision to minimize the congestion costs Z^* incurred by the IGO. Then, in order to attain the optimum in congestion management, the IGO must reward those transactions whose flows on line ℓ produce such an effect.

We can specify the usage charges for each transaction m. In the IGO-determined schedule, the flow $f_\ell^{*(m)}$ associated with transaction m in line l is approximated by

$$\hat{f}_\ell^{*(m)} \approx \varphi_\ell^{(m)} t^{(m)} + \sum_{k \in \mathcal{K}} \psi_{\ell,k} \, \Delta p_k^{*(m)} \tag{28}$$

where $\varphi_\ell^{(m)} t^{(m)}$ is the flow in line ℓ attributable to transaction m in the preferred schedule, and $\sum_{k\in\mathcal{K}} \psi_{\ell,k}\, \Delta p_k^{*(m)}$ is the change in the line flow that is due to the relief actions associated with transaction m. The usage charge to transaction m on line l is[5]

$$X_\ell^{(m)} = \chi_\ell^* \hat{f}_\ell^{*(m)}. \tag{29}$$

Note that this charge is imposed uniformly on all transactions that contribute to the overload and is consequently a nondiscriminatory charge.

The formulation of the congestion relief management problem in (16)–(26) has a number of important implications. The rule that the adjustment auction held by the IGO is voluntary allows each individual transaction a great deal of flexibility to decide its own transmission usage. For example, if a transaction wishes to ensure that it remains unaltered as a result of congestion relief actions, it may simply opt to let its selling generator(s) and buying load(s) not participate in the adjustment auction. Alternatively, if they do participate in the auction, they may set their offer prices at such a high level as to preclude their offers from being selected. We do not consider the trivial choice for any participant to set $\Delta p_k^{\min} = \Delta p_k^{\max} = 0$. Consequently, these transacting parties have to pay whatever usage charges may emanate from the auction. In other words, the transaction makes the explicit choice of its willingness to pay any price to have its transaction accommodated.

A particular transaction's decision to promote its own interests may lead to failure in the congestion management market. For example, there may be cases in which the IGO cannot remove overloads without the participation of a specific generator or load. Then, the absence of the participation of such an entity results in the congestion relief LP having no feasible solution. In such a case, the IGO must have the authority to order certain players to participate for the good of the entire system. Such entities can be *reliability must run (RMR)* units that receive payment for congestion relief service at the contractually negotiated price.

[5]The transmission tariff of a transmission provider such as an IGO typically includes a specified price for connection to the grid (access) and a periodic charge for transmission service (specified in units such as $/MW per month). These charges are specified and collected from all transmission customers. Congestion charges are in addition to these access and service charges.

TABLE I
THE OVERLOAD ALLOCATION RESULTS IN MW FOR THE TEST SYSTEM

Overloaded line		$\Delta f_1^{(m)}$ for transaction			
1	Δf_1	1	2	3	4
2	4.9	3.3	1.6	–	–
3	7.5	4.5	1.3	1.7	–
18	3.5	–	1.0	0.6	1.9

TABLE II
THE OFFER DATA IN THE IGO'S ADJUSTMENT AUCTION FOR THE TEST SYSTEM

offerer at bus k / offer data	Participants in trans. 3		Participants in trans. 4		Other participants	
	3	12	8	9	2	6
c_k^+ (\$/MWh)	25	25	30	15	20	22.5
c_k^- (\$/MWh)	10	20	15	7.5	8	10
Δp_k^{max} (MW)	20	15	20	20	10	15
Δp_k^{min} (MW)	–1 5	–17.5	–10	–25	–1 5	–5

TABLE III
THE $\psi_{\ell,k}$ VALUES

bus k / line ℓ	3	12	8	9	2	6
2	0.39	-0.15	0.23	0.21	0.13	0.28
3	0.18	-0.04	-0.22	-0.13	0.04	-0.41
18	0.36	-0.11	0.01	0.08	0.09	0.13

TABLE IV
THE OPTIMAL SOLUTION $\Delta p_k^{*(m)}$ IN MW

bus k / trans. m	participants in trans. 3		participants in trans. 4		other participants	
	3	12	8	9	2	6
1	-1.4	3.0	0	4.0	0	8.9
2	-0.8	0	0	0	-10.6	1.8
3	-1.3	5.0	0	0	0	3.1
4	-4.5	0	-4.0	0	-3.1	-0.1
net injection adjustments Δp_k^*	-8.0	8.0	-4.0	4.0	-13.7	13.7

IV. NUMERICAL RESULTS

We implemented and tested on several systems the proposed congestion management allocation scheme. The test systems varied in size from 14 to 300 buses and include networks based on the IEEE 300-bus, 118-bus, and 57-bus systems. We have chosen for illustrative purpose to focus on the IEEE 57-bus network-based test system to present the capabilities of the scheme and discuss some key policy implications. The test system with

TABLE V
THE TRANSMISSION USAGE CHARGES $\chi_\ell^{*(m)}$ AND TOTAL USAGE CHARGES $X^{*(m)}$

Line ℓ	χ_ℓ^* ($/MWh)	$f_\ell^{*(m)}$ (MW) / $X_\ell^{*(m)}$ ($/h) for transaction			
		1	2	3	4
2	98.4	70.4 / 6933	34.2 / 3362	-2.8 / -275	-36.4 / -3585
3	44.7	58.0 / 2613	17.0 / 764	22.0 / 990	-73.2 / -3299
18	129.9	-24.7 / -3202	17.1 / 2112	10.3 / 1336	31.6 / 4127
1	81.1	74.7 / 6054	34.9 / 2827	9.8 / 798	-37.2 / -3015
total usage charges $X^{*(m)}$ ($/h)		12,398	9,164	2,849	-5,773

the data given in Appendix B, has sufficient scope to illustrate the capabilities of the allocation mechanism. The results are representative and so not limited to systems of this size.

We first illustrate how the proposed overload allocation scheme attributes the overloads to the various transactions. Three lines 2, 3, and 18 are overloaded in the preferred schedule. These lines join buses 2 to 3, 3 to 4, and 3 to 15, respectively. The overload allocation results determined by (15) are summarized in Table I. For the congestion relief stage, we consider the generators at buses 2, 3, 8, 9, and 12 and the load at bus 6 as the participants in the IGO's adjustment auction. Then, $\mathcal{K} = \{2, 3, 6, 8, 9, 12\}$. Note that the generator at bus 2 and the load at bus 6, which participate in the adjustment market, are not parties in any of the four transactions. The offer data of the six offerers are given in Table II. The values of the $\psi_{\ell,k}$ associated with the overloaded lines and the adjustment auction buses are given in Table III. The LP optimal solution $\Delta p_k^{*(m)}$, $k \in \mathcal{K}$, $m \in \hat{\mathcal{M}}$ values in MW are tabulated in Table IV.

The optimal results indicate that transactions 3 and 4 are modified in the IGO-determined schedule. These modifications take into consideration the separation of markets constraint. In transaction 3(4), 8.0 MW(4.0 MW) of generation are redispatched from the generator at bus 3(8) to the generator at bus 12(9). The generator at bus 2 and the load at bus 6, which are not participants in transactions 3 and 4, cannot, however, participate in the modification of these two transactions. Transactions 1 and 2 remain unchanged in the IGO-determined schedules since none of the generators and loads of these transactions participates in the adjustment auction. This example clearly shows the impact of the separation of markets constraint in that the IGO, whose responsibility is to remove the congestion in order to maintain system reliability, is effectively prevented from intervening in the market.

The transmission usage price χ_ℓ^* and the total usage charges $X^{*(m)}$ charged to each transaction m are shown in Table V. The negative usage charges for a line indicate that the transaction is being reimbursed by the IGO for use of the line. The rationale for this payment is to induce, in effect, a counter flow in the line so as to be able to increase the dominant flow through the line.

We illustrate some of the latitude that the auction-based congestion management scheme provides to transactions. The voluntary nature of the adjustment auction allows a transaction to decide on its own whether or not to participate and how to construct its offer effectively so as to achieve the desired portfolio in the IGO-determined schedule. Consider in the test system that transaction 4 that is modified in the IGO-determined schedule. To reflect that transaction 4 desires to remain unchanged, the transaction raises the price c_9^+ offered by its generator at bus 9 from $15/MWh to $35/MWh, making it the most expensive bidder in the auction. The modified LP problem solution with the increased c_9^+ has $\Delta p_9^* = \Delta p_8^* = 0$ leaving transaction 4 unchanged. However, the decision by transaction 4 to raise c_9^+ results in changes in the total usage charges $X^{*(m)}$ paid by each transaction m. The modified usage payments show that while the IGO's usage payment to transaction 4 decreases by $3343/h, the usage charges paid by the other transactions decrease.

While the auction-based congestion management mechanism allows transactions a great deal of freedom, the decision made by a market participant according to its own interests may disadvantage the system or even result in the failure of the IGO's congestion relief. For example, suppose that the generator at bus 8 of transaction 4 decides not to participate in the adjustment auction. Consequently, Δp_8 stops being a decision variable for the LP problem. We assume that all the other offerers and their offers remain unchanged. Without the presence of Δp_8 as a decision variable for the IGO, however, the LP problem is infeasible. The overloads cannot be removed from the network in this case for the set of offers received. Consequently, in order to ensure that the indispensable relief services from the generator at bus 8 are available, the IGO must designate it as an RMR unit and pay for its relief service at the contractually negotiated price.

V. Concluding Remarks

In this paper, we have developed a physical-flow-based congestion management allocation scheme for multiple transaction networks. The work in this paper gives rise to several topics that require further investigation. One of the chief simplifications made in the paper is the representation of all the transmission constraints in terms of line flow limits. Since such a simplifying modeling approach may be inadequate, particularly for the case in which the transmission system congestion is due to voltage or stability limits, more realistic models that can explicitly represent the congestion in terms of the voltage or stability constraints are required. The nonlinear and nonseparable nature of the expression for the voltage or stability limit violation makes the allocation issue an extremely challenging problem. The consideration of contingency needs to be incorporated into the congestion management to take into account

TABLE VI
THE TRANSACTION PROFILES OF THE TEST SYSTEM

trans. m	$t^{(m)}$ (MW)	$\mathcal{S}^{(m)}$	$\mathcal{B}^{(m)}$
1	282	$\{(1,100\%)\}$	$\{(2,1\%),(3,15\%),(5,4\%),(6,27\%),(8,53\%)\}$
2	197	$\{(1,100\%)\}$	$\{(9,61\%),(10,3\%),(13,9\%),(14,5\%),(16,22\%)\}$
3	322	$\{(3,12\%),(12,88\%)\}$	$\{(15,7\%),(17,13\%),(18,8\%),(19,1\%),(23,2\%),(25,2\%),(27,3\%),(28,1\%),(29,5\%),(30,1\%),(31,2\%),(33,1\%),(35,2\%),(38,4\%),(41,2\%),(42,2\%),(44,4\%),(47,9\%),(49,6\%),(50,7\%),(51,6\%),(52,2\%),(53,6\%),(54,1\%),(57,1\%)\}$
4	450	$\{(8,78\%),(9,22\%)\}$	$\{(1,12\%),(12,84\%),(55,2\%),(57,2\%)\}$

those cases in which the system is not congested under the base case condition but becomes so under certain specified contingencies. Since the number of the contingencies specified may be large, the explicit incorporation of contingencies into the allocation and relief development may require considerable effort to address effectively computational aspects for a numerically tractable scheme. Progress on these and related topics will be reported in future papers.

APPENDIX A
THE TRANSACTION FRAMEWORK-BASED DC POWER FLOW

We consider a system of $N+1$ buses with bus 0 being designated as the slack bus. We denote by $\underline{\hat{\theta}} = [\hat{\theta}_1, \hat{\theta}_2, \ldots, \hat{\theta}_N]^T$ the voltage angle vector computed by the dc power flow. Let $\underline{\hat{B}}$ be the $N \times N$ submatrix of the $(N+1)$-node (augmented) network susceptance matrix $\underline{B}$ [11]. Without any loss of generality we may set $\hat{\theta}_0 = 0$. The dc power flow formulation of the transaction-based network then is

$$\underline{\hat{B}}\,\underline{\hat{\theta}} = \underline{p} = -\sum_{m\in\mathcal{M}} \underline{\delta}^{(m)} t^{(m)} \tag{A1}$$

where $\underline{p} \triangleq [p_1, p_2, \ldots, p_N]^T$ is the vector of the net nodal injection. Let

$$\underline{D} = [d_{ij}] = \underline{\hat{B}}^{-1}. \tag{A2}$$

Then

$$\hat{\theta}_n = -\sum_{k=1}^{N} d_{nk} p_k = -\sum_{m\in\mathcal{M}} \sum_{k=1}^{N} d_{nk}\, \delta_k^{(m)} t^{(m)} \qquad n = 1, 2, \ldots N. \tag{A3}$$

Let us rewrite (A3) as

$$\hat{\theta}_n = \sum_{m\in\mathcal{M}} \mu_n^{(m)} t^{(m)}, \qquad n = 1, 2, \ldots N \tag{A4}$$

where we define, for $n = 1, 2, \ldots N$

$$\mu_n^{(m)} = -\sum_{k=1}^{N} d_{nk}\, \delta_k^{(m)} = \sum_{j=1}^{N_b^{(m)}} d_{nb_j^{(m)}} \beta_j^{(m)} - \sum_{i=1}^{N_s^{(m)}} d_{ns_i^{(m)}} \sigma_i^{(m)}. \tag{A5}$$

For completeness, we define $\mu_0^{(m)} = 0$, $m \in \mathcal{M}$, $d_{n0} = 0$, $n = 1, 2, \ldots N$. Then, for $i \neq j$,

$$\hat{\theta}_i - \hat{\theta}_j = \sum_{m\in\mathcal{M}} \pi_{ij}^{(m)} t^{(m)}, \qquad i, j = 0, 1, 2, \ldots, N \tag{A6}$$

with

$$\pi_{ij}^{(m)} = \mu_i^{(m)} - \mu_j^{(m)}, \qquad m \in \mathcal{M},\ i, j = 0, 1, \ldots, N. \tag{A7}$$

We may also rewrite (A6) as

$$\hat{\theta}_i - \hat{\theta}_j = \sum_{k=1}^{N} (d_{kj} - d_{ki}) p_k. \tag{A8}$$

APPENDIX B
THE TEST SYSTEM

The test system is constructed on the basis of the IEEE 57-bus system. We use the generation/load data of the 57-bus system to construct four transactions. The transaction profiles are tabulated in Table VI.

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