CONGESTION MANAGEMENT ALLOCATION IN MULTIPLE TRANSACTION NETWORKS

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Abstract: 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. We present an adjustment auction-based congestion relief mechanism that enables the Independent Grid Operator (IGO) to acquire relief services to remove the overload congestion attributed to each transaction from the network in the most economic manner. This congestion relief scheme determines the nondiscriminatory transmission charges for each transaction's usage of the network. We illustrate the workings of the proposed scheme using the IEEE 57-bus system and discuss the policy implications of the congestion relief and allocation solution.

Keywords: Congestion Management, multiple transaction networks, open access transmission regimes, transmission pricing

1. 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 the 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.

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 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 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.

In this paper, we develop a physical-flow-based congestion management allocation scheme to determine the contribution to the overload congestion attributed to each transaction. While the issue of allocation is one that the multiple transactions must deal with each time congestion relief is necessary, the allocation problem has not been addressed up to now. The objective of the paper is to present a physically reasonable scheme to appropriately allocate congestion among the transactions that cause the congestion. The congestion relief scheme provides the IGO with an effective tool with which the IGO acquires the congestion relief services to remove each transaction's congestion contribution at least cost. The proposed scheme is general and can accommodate different market rule specifications. The scheme permits each transaction to make its own transmission usage decisions and provides the transaction with efficient price signals for this task. The paper consists of three additional sections. Section 2 focuses on the development of an allocation mechanism to determine the allocation attributed to each transaction of its contribution to the network congestion. Section 3 formulates the IGO's least–cost congestion relief problem. We present the optimality analysis and develop the transmission usage pricing scheme. Section 4 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, the real-time congestion relief is outside the scope of the paper. The long-term solution to congestion through the transmission system expansion is also not addressed here.

2. 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) $\mathcal{S}^{(m)}$ 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

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

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 $\sigma_i^{(m)} \in [0,1]$, $i = 1,2,..N_s^{(m)}$, where $N_s^{(m)}$ is the number of selling buses in transaction *m*. Similarly, $\mathcal{B}^{(m)}$ is the collection of 2-tuples

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

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 $\beta_j^{(m)} \in [0,1]$, $j = 1,2,..N_b^{(m)}$, where $N_b^{(m)}$ is the number of buying buses in transaction *m*.

We characterize transmission congestion within this framework and then determine the contribution to congestion attributable to each transaction. We denote by 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 $\ell \in L$. 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. Let $\tilde{L} \subset L$ be the subset of overloaded lines, i.e.,

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

and let $D f_l$ denote the overload in line $\ell \in \tilde{L}$:

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

Consider the overloaded line $\ell \in \tilde{L}$. 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 $g_{ij} \underline{\underline{D}}\, r_{ij} / (r_{ij}^2 + x_{ij}^2)$ and $b_{ij} \underline{\underline{D}}\, x_{ij} / (r_{ij}^2 + x_{ij}^2)$. The voltage magnitude V_n and angle q_n for buses $n = 1,2,...,N$ are a function of M [1]. Then, the line flow f_ℓ from bus *i* to bus *j* is given by

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

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

$$\tilde{f}_\ell = \left[g_{ij}(q_i - q_j)/2 + b_{ij} \right](q_i - q_j) , \tag{7}$$

Next, we define $\underline{\hat{q}} = [\hat{q}_1, \hat{q}_2, ..., \hat{q}_N]^T$ as the voltage angle vector computed by the DC power flow. Without any loss of generality, we may set to 0 the value of $\hat{q}_0$ at the slack bus. Then,

$$\hat{q}_i - \hat{q}_j = \sum_{m \in M} p_{ij}^{(m)} t^{(m)} ,\ i, j = 0,1,2,..., N, i \neq j , \tag{8}$$

with the definition of $p_{ij}^{(m)}$ 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

$$\begin{aligned} \hat{f}_\ell &= \left[g_{ij}(q_i - q_j)/2 + b_{ij} \right](\hat{q}_i - \hat{q}_j) \\ &= \left[g_{ij}(q_i - q_j)/2 + b_{ij} \right] \sum_{m \in M} p_{ij}^{(m)} t^{(m)} \\ &= \sum_{m \in M} \left\{ [g_{ij}(q_i - q_j)/2 + b_{ij}] p_{ij}^{(m)} \right\} t^{(m)} . \end{aligned} \tag{9}$$

If we define for each $m \in M$

$$j_\ell^{(m)} \triangleq \left[g_{ij}(q_i - q_j)/2 + b_{ij} \right] p_{ij}^{(m)} \tag{10}$$

then[1],

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

In (11), we may consider $j_\ell^{(m)} t^{(m)}$ to be the flow attributable to transaction *m* in the preferred schedule with the sign of $j_\ell^{(m)}$ indicating the direction of the contribution to the flow f_ℓ associated with transaction *m.* For each overloaded line ℓ, we partition M into two non-intersecting subsets D_ℓ and C_ℓ :

$$D_l \triangleq \left\{ m \in M : j_\ell^{(m)} \geq 0 \right\},\ C_l \triangleq \left\{ m \in M : j_\ell^{(m)} < 0 \right\} \tag{12}$$

Thus, D_ℓ 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, C_ℓ 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

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

Since each transaction in 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 C_l results in counter flows and the flows, in effect, increase the line flow limit from $f_\ell^{\max}$ to

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[1] Note that if we assume that $r_{ij} << x_{ij}$ and that $\left| q_i - q_j \right|$ is small, then $g_{ij} \left| q_i - q_j \right| / 2 << b_{ij} \approx 1/x_{ij}$. Consequently, $j_\ell^{(m)} \approx p_{ij}^{(m)} / x_{ij}$ so that the approximation in (11) is relatively straightforward to compute.

$f_\ell^{\max} + [\sum_{m \in C_\ell} - j_\ell^{(m)} t^{(m)}]$. So the line ℓ overload is attributed in its entirety to the transactions in D_ℓ.

We define for each transaction $m \in M$

$$\tilde{L}^{(m)} \triangleq \left\{ \ell : \ell \in \tilde{L} \text{ and } j_\ell^{(m)} \geq 0 \right\}, \qquad (14)$$

the subset of overloaded lines with the associated flows that contribute to the dominant flows in the lines. Note that for a given *m*, $\tilde{L}^{(m)}$ may be empty. Let $\hat{M} = \bigcup_{\ell \in \tilde{L}} D_\ell$. Then $\hat{M} \subset M$ 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 D_ℓ, then the contribution to the total overload Δf_ℓ attributable to transaction $m \in D_\ell$ is

$$\Delta f_\ell^{(m)} = \frac{j_\ell^{(m)} t^{(m)}}{\sum_{m' \in D_\ell} j_\ell^{(m')} t^{(m')}} \Delta f_\ell \approx \frac{j_\ell^{(m)} t^{(m)}}{\sum_{m' \in D_\ell} j_\ell^{(m')} t^{(m')}} \Delta \tilde{f}_\ell \qquad (15)$$

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

3. 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 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 Dp_k. Note that while a generator may provide Dp_k by increasing or decreasing its production output, a load may also effectively offer Dp_k by varying its demand by $-Dp_k$. The incremental injection $Dp_k > 0$ (decremental injection $Dp_k < 0$) offer has a charge of c_k^+ \$ / MW (a rebate of c_k^- \$ / MW) [2]. 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 $Dp_k \in [Dp_k^{\min}, Dp_k^{\max}]$. If the IGO accepts the offer of the participant at bus k, then it pays $c_k^+ Dp_k$ for $Dp_k \geq 0$ to, or receives $-c_k^- Dp_k$ for $Dp_k < 0$ 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[3]. The decision variables for the IGO are the relief actions $Dp_k^{(m)}, k \in K, m \in \hat{M}$. $Dp_k^{(m)}$ is the net incremental/decremental injection acquired from the bidder at bus k for transaction m to relieve the overload burden $Df_\ell^{(m)}, \ell \in \tilde{L}^{(m)}$ attributed to the transaction *m*. The IGO's objective function is to

$$\min \; Z = \sum_{k \in K} c_k \left[\sum_{m \in \hat{M}} Dp_k^{(m)} \right] \qquad (16)$$

where

$$c_k = \begin{cases} c_k^+ & \text{if } Dp_k = \sum_{m \in \hat{M}} Dp_k^{(m)} \geq 0 \\ c_k^- & \text{otherwise} \end{cases} \qquad (17)$$

We use a small signal model to analyze the effects on the transmission network of $Dp_k^{(m)}, k \in K, m \in \hat{M}$. This is reasonable because $Dp_k^{(m)}$ are typically small changes in the net injections at the buses $k \in K$ 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 $Dp_k^{(m)}$. From the approximation $\tilde{f}_\ell$ of f_ℓ in (7), we obtain

$$\frac{\partial f_\ell}{\partial p_k} \approx \frac{\partial \tilde{f}_\ell}{\partial p_k} = \left[g_{ij}(q_i - q_j) + b_{ij} \right] \left(\frac{\partial q_i}{\partial p_k} - \frac{\partial q_j}{\partial p_k} \right)$$

$$\approx \left[g_{ij}(q_i - q_j) + b_{ij} \right] \left(\frac{\partial \hat{q}_i}{\partial p_k} - \frac{\partial \hat{q}_j}{\partial p_k} \right) \qquad (18)$$

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

[3] 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.

It follows from (A8) in Appendix A that

$$\frac{\partial \hat{q}_i}{\partial p_k} - \frac{\partial \hat{q}_j}{\partial p_k} = d_{kj} - d_{ki} \quad (19)$$

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

$$y_{\ell,k} \underline{\underline{D}} [g_{ij}(q_i - q_j) + b_{ij}](d_{kj} - d_{ki}) \quad (20)$$

Since $y_{\ell,k} \approx \frac{\partial f_\ell}{\partial p_k}$, $y_{\ell,k}$ 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 the followings:

(i) *power balance*:

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

(ii) *removal of overloads*:

$$-\sum_{k \in K} y_{\ell,k} \Delta p_k^{(m)} = \Delta f_\ell^{(m)}, \ell \in \tilde{L}^{(m)}, m \in \hat{M} \quad (22)$$

(iii) *no overloads in the IGO schedule*:

$$f_\ell + \sum_{k \in K} y_{\ell,k} \Delta p_k \leq f_\ell^{\max}, \ell \in L \quad (23)$$

(iii) *increment/decrement limits*:

$$Dp_k^{\min} \leq Dp_k^{(m)} \leq Dp_k^{\max}, \quad k \in K \quad (24)$$

(iv) *total increment/decrement limits*:

$$\Delta p_k^{\min} \leq \Delta p_k \leq \Delta p_k^{\max}, \ k \in K, \ m \in \hat{M} \quad (25)$$

(vi) *separation of markets*:

$$\sum_{k \in S^{(m)} \cup B^{(m)}} \Delta p_k = 0, \ m \in \hat{M} \quad (26)$$

The equality constraints in (22) indicate that the IGO acquires the relief actions from the participants in the adjustment bidding to reduce the flow in line ℓ by exactly the $\Delta f_\ell^{(m)}$ overload attributed to transaction $m \in D_\ell$. 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 formulation in (16)-(26) obtains a linear program 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), $\sum_{m \in \hat{M}} Dp_k^{(m)}$ is replaced by Dp_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 $r_l^{*(m)}$ and m_l^*, respectively. Note that $m_\ell^* \geq 0$. We consider the sensitivity $c_\ell^* = -\partial Z^*(f_\ell^{\max}) / \partial f_\ell^{\max} = \partial Z^*(f_\ell) / \partial f_\ell$.

We use the LP formulation to evaluate

$$c_\ell^* = \begin{cases} m_\ell^* + \sum_{m \in D_\ell} \left[\frac{r_\ell^{*(m)} j_\ell^{(m)} t^{(m)}}{\sum_{m' \in D_\ell} j_\ell^{(m')} t^{(m')}} \right] & \text{if } \ell \in \tilde{L} \\ m_\ell^* & \text{otherwise} \end{cases} \quad (27)$$

For $\ell \in \tilde{L}$, one unit decrease in $f_\ell^{\max}$ results in an increase of $\frac{j_\ell^{(m)} t^{(m)}}{\sum_{m' \in D_\ell} j_\ell^{(m')} t^{(m')}}$ in the congestion burden associated with each transaction $m \in D_\ell$. Thus, the first component of c_ℓ^* in (26) is the sum of the additional congestion expenditures incurred by the IGO in relieving the increased congestion burdens. The expenditures m_ℓ^* are incurred to ensure that there is no overload in the IGO-determined schedule. We may use c_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 c_ℓ^* may be negative for some $\ell \in \tilde{L}$. The physical interpretation of a negative c_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

$$\hat{f}_\ell^{*(m)} \approx j_\ell^{(m)} t^{(m)} + \sum_{k \in K} y_{\ell,k} Dp_k^{*(m)} \qquad (28)$$

where $j_\ell^{(m)} t^{(m)}$ is the flow in line ℓ attributable to transaction *m* in the preferred schedule, and $\sum_{k \in K} y_{\ell,k} \Delta p_k^{*(m)}$ 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

$$X_\ell^{(m)} = c_\ell^* \hat{f}_\ell^{*(m)} \qquad (29)$$

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

4. NUMERICAL RESULTS

We implemented and tested on several systems the proposed congestion management allocation scheme. We illustrate the capabilities of the scheme and discuss some key policy implications using the system described in Appendix B derived from the IEEE 57-bus network with four transactions.

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 1. For the congestion relief

Table 1. The overload allocation results in MW for the test system [4]

Overloaded line		$\Delta f_\ell^{(m)}$ for transaction			
ℓ	Δf_ℓ	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

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, $K = \{2, 3, 6, 8, 9, 12\}$. The offer data of the six offerers are given in Table 2. The values of the

Table 2. 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)	-15	-17.5	-10	-25	-15	-5

$y_{\ell,k}$ associated with the overloaded lines and the adjustment auction buses are given in Table 3. The LP optimal solution $Dp_k^{*(m)}$, $k \in K$, $m \in \hat{M}$ values in MW are tabulated in Table 4.

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

Table 3. The $y_{l,k}$ 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 4. The optimal solution $Dp_k^{*(m)}$ 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

[4] A dash entry in Table 1 indicates that transaction *m* does not contribute to the overload in the specific line.

Table 5. The transmission usage charges $c_\ell^{*(m)}$ and total usage charges $\chi^{*(m)}$

Line ℓ	c_ℓ^* ($/MWh)	$f_\ell^{*(m)}$ (MW) / $C_\ell^{*(m)}$ ($/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 $\chi^{*(m)}$ ($/h)		12,398	9,164	2,849	-5,773

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 c_ℓ^* and the total usage charges $\chi^{*(m)}$ charged to each transaction *m* are shown in Table 5. 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 $\chi^{*(m)}$ 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 does not have even a feasible solution. It means that the overloads cannot be removed from the network in this case with 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 a *reliability must run* unit and pay for its relief service at the contractually negotiated price.

5. CONCLUSIONS

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 development of the congestion management allocation scheme 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 development of an allocation mechanism of transmission congestion caused by voltage or stability constraints constitutes a major challenge. The consideration of contingency needs to be incorporated into the congestion management to take into account those cases where the system is not congested under the normal condition but becomes so under certain specified contingencies. This problem will require considerable effort to address the modeling and computational aspects.

6. REFERENCES

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7. ACKNOWLEDGEMENT

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BIOGRAPHIES

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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 $\underline{\hat{q}} = [\hat{q}_1, \hat{q}_2, ..., \hat{q}_N]^T$ 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 (argumented) network susceptance matrix $\underline{B}$ [11]. Without any loss of generality we may set $\hat{q}_0 = 0$. The DC power flow formulation of the transaction-based network then is

$$\underline{\hat{B}}\,\underline{\hat{q}} = \underline{p} = -\sum_{m \in M} \underline{d}^{(m)} t^{(m)} \qquad \text{(A1)}$$

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

$$\underline{D} = [d_{ij}] = \underline{\hat{B}}^{-1} \qquad \text{(A2)}$$

Then,

$$\hat{q}_n = -\sum_{k=1}^{N} d_{nk} p_k = -\sum_{m \in M} \sum_{k=1}^{N} d_{nk} d_k^{(m)} t^{(m)},\ n = 1,2,...N \qquad \text{(A3)}$$

Let us rewrite (A3) as

$$\hat{q}_n = \sum_{m \in M} m_n^{(m)} t^{(m)},\ n = 1,2,...N \qquad \text{(A4)}$$

where we define, for $n = 1,2,...N$,

$$m_n^{(m)} = -\sum_{k=1}^{N} d_{nk} d_k^{(m)} = \sum_{j=1}^{N_b^{(m)}} d_{nb_j^{(m)}} b_j^{(m)} - \sum_{i=1}^{N_s^{(m)}} d_{ns_i^{(m)}} s_i^{(m)} \quad \text{(A5)}$$

For completeness, we define $m_0^{(m)} = 0, m \in M$, $d_{n0} = 0, n = 1,2,... N$. Then, for $i \neq j$,

$$\hat{q}_i - \hat{q}_j = \sum_{m \in M} p_{ij}^{(m)} t^{(m)}, i, j = 0, 1, 2,..., N . \quad \text{(A6)}$$

with

$$p_{ij}^{(m)} = m_i^{(m)} - m_j^{(m)}, m \in M, i, j = 0, 1,..., N \quad \text{(A7)}$$

We may also rewrite (A6) as

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

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 B1.

Table B1. The transaction profiles of the test system

trans. m	$t^{(m)}$ (MW)	$S^{(m)}$	$B^{(m)}$
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	$\{(8,78\%),(9,22\%)\}$	$\{(1,12\%),(12,84\%),(55,2\%),(57,2\%)\}$