

Transaction Based Power Flow Analysis For Transmission Utilization Allocation

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Abstract: This paper proposes a framework of transaction based power flow analysis (TBPF) for transmission utilization allocation. The TBPF utilizes distributed purchase-sale pairs to replace the role of a single slack bus on energy imbalance during power flow calculation iterations. To compare with conventional power flow analysis, accurate allocation of use-of-transmission is part of a TBPF solution. In particular, the TBPF is able to identify interaction components among transactions as well as the effect of reactive power on transmission losses and active power flows. Two allocation rules for cross terms are proposed to hedge firm or existing transactions against market risk. The standard WSCC 9 bus system is used to demonstrate the performance of the TBPF.

Index terms: Bilateral transaction, loss allocation, power exchange, power flow, use-of-transmission

I. INTRODUCTION

While the electric power industry moves into an era of supply competition and consumer choice, the power system evolves towards competitive operating paradigm. As a legacy, the conventional power flow analysis remains one of major evaluation tools for energy trading and scheduling in the existing PoolCo. markets. However, it has major shortcomings to adapt to the emerging power market in some aspects: (i) the system operator (say ISO) has no authority to designate a unique generator as the slack bus for the whole electricity market at the ex ante phase; (ii) MW generations are decided by bilateral contracts and other mechanism, and not totally rely on a centralized economic dispatch (ED); (iii) the pool-like power exchange markets (PX) and bilateral contract transactions (BC) share the same transmission system, and their own responsibility on losses and branch flows need be fairly and accurately evaluated; (iv) individual scheduling coordinators (SCs) are entitled to match energy imbalance for their own transactions; (v) the ISO coordinates regional reactive power markets to support energy delivery in the transmission grid etc.

With unbundling of generation and transmission services, it is essential to allocate transmission utilization for different market players. At the present stage, the GAPP method sponsored by NERC is widely used by the utilities or PoolCo. However, it is only limited to DC power flow analysis. Recent research efforts focus on AC powerflow based allocation technologies. Some important contributions are summarized as follows. In the so-called coordinated multi-

lateral trade model [1], a quadratic loss formula is proposed to allocate transmission loss. It has the ability to find interactive loss components among energy trades. Alternatively, an integration scheme is presented to allocate transmission losses for bilateral transactions [2]. Given a path along which the transactions vary with time, the loss allocation is unique and exact by this method. The integration scheme also has extensive potentials for allocations of MW flows, MVar flows and losses, not limited to real loss allocations. However, precise solution of the integration algorithm is time consuming, and allocation results heavily rely on the adopted integration path. A simple sensitivity factor GGDF based approach is implemented to allocate supplemental transmission cost for individual generators in the real-life power market [3]. Several popular electricity flow tracing techniques are founded in [4] and [5]. The methods topologically determine contributions of individual generators to loads and flows upon the so-called proportional sharing principle. The electricity flow tracing does not account for Kirchhoff Voltage Law, and is limited to active power flows. A proposal of network flow decomposition is presented in [6]. As an engineering-based approach, it provides valuable insights on how to decompose complex power flows into transaction components by simple linear manipulation. Our extensive research finds that the accuracy of the proposed flow decompositions is compromised due to several key aspects: (i) reactive power support of a sending generator may not be solely consumed by its own sinking load, in stead, local reactive loads and network reactive loss usually takes up most reactive power support of the generator; (ii) The accuracy of flow decompositions may become a question in cases of shunt terms $b_i \neq 0$; (iii) the selection of a single slack bus or specification of generation participation factors remains a controversial issue in the deregulated power market.

Accordingly, this paper develops a framework of transaction based power flow analysis for more accurate AC powerflow decompositions. Our approach utilizes a concept of transaction pairs to substitute the role of the slack bus on matching energy imbalance. The transaction pair is introduced in [7]. Its basic properties are restated here: (1) a transaction pair represents an actual purchase-sale schedule, consisting of sending generators and sinking loads; (2) an ideal transaction pair can be self-balancing, i.e., its net energy production covers its associated loads plus transmission loss charge (i.e., to reach such an energy balance, a transaction can turn to increase its real generation amounts at the delivery points or curtail its load demand at the sinking points); (3) if the buyer would like to buy losses on specified generators, it should also be arranged; (4) a transaction pair may not

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maintain reactive power balance by itself, and reactive power scheduling is more than an energy purchase-sale agreement. A system-wide support is needed. Beside bilateral energy transactions, a centrally dispatched regional power pool may be aggregated into transaction pairs when impacts of neighboring systems on the pool are considered. The employment of transaction pairs enables market separation between pool-like power exchange market and bilateral transactions. Though it is agued that market separation constraint may affect the global optimal dispatch in the real-time balancing market, but it enforces energy trading agreement, fosters fair market competition, makes bilateral transactions more stable, and simplifies financial filling [8].

With the assumed transaction pairs, a framework of transactions-based power flow analysis (TBPF) is described in section II. Potential applications of the TBPF are illustrated in section III by the WSCC 9 bus system. A short discussion ends this paper in section IV.

II. MATHEMATICAL FORMULATION

A. Notation

N : The set of all buses in the system.

L : The set of all branches (transmission lines, transformers, etc.) in the system.

T_{PX} : The set of all central power exchange (PX) markets in the system.

T_{BC} : The set of all point-to-point (PTP) or bilateral contract (BC) type energy transactions in the system.

K : The set of all energy transactions (i.e., $K = T_{PX} \cup T_{BC}$).

Q : An area-wide reactive power scheduling coordinator (market).

Y_{bus} : A full-dimension nodal admittance matrix together with all bus and line shunt terms (i.e., b_0/b_c), in which the entry of a branch connecting nodes i with j is expressed by $y_{ij} = g_{ij} - jb_{ij}$. Normally, the matrix of Y_{bus} is invertible for a general transmission network.

Z_{bus} : A full-dimension nodal impedance matrix ($= [Y_{bus}]^{-1}$).

E_{bus} : Complex bus voltage vector, where entry is expressed by $E_i = V_i e^{j\theta_i}$.

I_{bus} : Complex nodal injection current vector.

f : The index of “from” buses of the branches.

t : The index of “to” buses of the branches.

E_f, E_t : The “from/to” complex nodal voltage vector.

I_f, I_t : The “from/to” complex branch current vector.

To simplify matrix representation of the branch power flow, we define three diagonal branch admittance matrices:

$\text{diag}(Y_s)$: A diagonal matrix with $(L \times L)$ dimension, whose elements are series admittance of each branch.

$\text{diag}(B_c)$: A diagonal matrix with $(L \times L)$ dimension, whose elements are half line charging susceptance.

$\text{diag}(T_{ap})$: A diagonal matrix with $(L \times L)$ dimension, whose elements are either 1.0 (i.e., lines) or actual ratio values (i.e., common transformers or phase-shifters).

Four branch admittance matrices with $(L \times L)$ dimension are constructed accordingly.

$$\begin{aligned} Y_{tt} &= \text{diag}(Y_s) + j \times \text{diag}(B_c) \\ Y_{ff} &= Y_{tt} \times (\text{diag}(T_{ap}) \times \text{diag}(T_{ap})^*)^{-1} \\ Y_{ft} &= -\text{diag}(Y_s)^* \times (\text{diag}(T_{ap})^*)^{-1} \\ Y_{tf} &= -\text{diag}(Y_s) \times (\text{diag}(T_{ap}))^{-1} \end{aligned} \quad (1)$$

Where both non-standard ratio of the transformer and complex ratio of the phase-shifter are located at the “from” side of the branch.

B. Definition

In general, an energy transaction k is defined as a pair of transaction vector (P_G^k, P_D^k) , representing real power generation schedule and real demand schedule of this transaction, respectively. In particular,

$$\begin{aligned} P_G^k &= [P_{G,1}^k \ P_{G,2}^k \ \dots \ P_{G,n-1}^k \ P_{G,n}^k]^T \\ P_D^k &= [P_{D,1}^k \ P_{D,2}^k \ \dots \ P_{D,n-1}^k \ P_{D,n}^k]^T \end{aligned} \quad (2)$$

As a transaction pair, the summation of P_G^k is assumed to match that of P_D^k in response to the signed economic contract. Similarly, reactive demand of the consumer and reactive generation of the supplier can be represented by

$$\begin{aligned} Q_G^k &= [Q_{G,1}^k \ Q_{G,2}^k \ \dots \ Q_{G,n-1}^k \ Q_{G,n}^k]^T \\ Q_D^k &= [Q_{D,1}^k \ Q_{D,2}^k \ \dots \ Q_{D,n-1}^k \ Q_{D,n}^k]^T \end{aligned} \quad (3)$$

However, there is no direct economic agreement between Q_G^k and Q_D^k in general, since the reactive power generation of individual generator installed with automatic voltage regulation function (AVR) is operated based upon the voltage control requirement of the system.

C. Assumptions

- 1) Each energy transaction must balance its own generations and loads (plus its share of transmission loss).
- 2) Reactive power scheduling is a separate market.
- 3) A single system-wide reactive power market is responsible for all reactive power delivery in the system.

D. Problem formulation

In general, the TBPF problem is modeled as follows,

$$\begin{aligned} \sum_{k \in K} (P_{G,i}^k - P_{D,i}^k) &= V_i \sum_{j \in i} V_j (g_{ij} \cos \mathbf{q}_{ij} + b_{ij} \sin \mathbf{q}_{ij}) \\ \sum_{k \in K} (Q_{G,i}^k - Q_{D,i}^k) &= V_i \sum_{j \in i} V_j (g_{ij} \sin \mathbf{q}_{ij} - b_{ij} \cos \mathbf{q}_{ij}) \end{aligned} \quad (4)$$

for $i = 1, 2, 3, \dots, r-1, r+1, \dots, n$ (r-reference bus)

Additional market separation constraints are introduced to enforce Assumption 1. Namely,

$$P_{G,s}^k + \sum_{i \in N \wedge i \neq s} P_{G,i}^k = \sum_{i \in N} P_{D,i}^k + P_{Tloss}^k \quad \text{foreach } k \in K \quad (5)$$

Where P_{Tloss}^k is the summed transmission loss charge to energy transaction k generator; s is selected as the slack generator for transaction k , whose real generation is responsible to match energy imbalance of this transaction during power flow calculation. Meanwhile, energy production of the remaining generators in the same transaction is specified at ex ante phase, and remains unchanged through the real-time trading process under the normal operation condition.

To efficiently solve the above augmented power flow equations, we next derive an exact loss formula to allocate transmission losses for individual energy transactions.

We begin with an initial operating point (V_0, \mathbf{q}_0) , where all energy transactions are charged with no transmission loss share, with one exception that the transaction designated as a reference bus temporarily takes on all transmission losses of the system.

To overcome nonlinear characteristics of real and reactive power equations, we translate all power injections into complex valued nodal current injection vector I_{bus} by

$$[I_{bus}] = [Y_{bus}] \times [E_{bus}] \quad (6)$$

We would like to further decompose I_{bus} into components that are associated with the scheduled energy transactions and ISO-dominated reactive power market.

In practice, the complex current injections from an energy transaction pair k , represented by (P_G^k, P_D^k) can not be identified from the power flow solution, since all transactions are physically coupled with one another by the bus voltage of the system.

However, the current injections of energy transaction k can be approximated as follows

$$I^k \approx [\text{diag}(E_{bus}^*)]^{-1} \times [P_G^k - P_D^k], \quad \text{for each } k \in K \quad (7)$$

Where $\text{diag}(E_{bus}^*)$ is a diagonal matrix, whose elements are complex conjugate of nodal voltage values.

Note that imaginary part of the matrix I^k contains dominant components coupled with the reactive power market. To reduce the coupling effects, we therefore remove imaginary part of the original matrix I^k to account for the transaction.

$$I_r^k \approx \text{Re}(I^k) \quad (8)$$

As it is assumed that the central reactive power market covers all reactive power loads and generations and is responsible for the system reactive power balance, the associated current injections become

$$I^Q \approx I_{bus} - \sum_{k \in K} I_r^k \quad (9)$$

$$\text{or } I^Q \approx [\text{diag}(E_{bus}^*)]^{-1} \times [Q_G^k - Q_D^k] + \sum_{k \in K} \text{Im}(I^k)$$

With decomposed nodal current injection vector, we next determine the impact of each transaction on bus voltage. According to the **Kirchhoff** Law, the induced voltage of energy transaction k (denoted by E^k) can be derived by

$$E^k = [Y_{bus}]^{-1} \times I_r^k, \quad \text{for each } k \in K \quad (10)$$

Reactive power support of the system can be evaluated by

$$E^Q = [Y_{bus}]^{-1} \times I^Q \quad (11)$$

Since reactive power dominates bus voltage magnitudes, normally, we have

$$|E_i^Q| \gg |E_i^k| \quad \text{and} \quad |E_i^Q| \approx |E_{bus,i}| \approx 1, \quad \text{for each } i \in N \quad (12)$$

In the next, we decompose transmission system usage into individual transaction components by applying the E^k and E^Q directly.

To compute the decomposed flows and losses, we denote “from” and “to” bus voltage vectors E_f, E_t according to index f and index s , respectively.

Let I_f, I_t represent branch current vectors injected at “from” and “to” buses of the branches. We have

$$\begin{bmatrix} I_f \\ I_t \end{bmatrix} = Y_{aug} \times \begin{bmatrix} E_f \\ E_t \end{bmatrix}, \quad \text{where } Y_{aug} = \begin{bmatrix} Y_{ff} & Y_{ft} \\ Y_{tf} & Y_{tt} \end{bmatrix} \quad (13)$$

Let S_f, S_t represent complex branch power flow vectors at “from” and “to” buses of each branch, we have

$$S_f = \text{diag}(E_f) \times I_f^*, \quad S_t = \text{diag}(E_t) \times I_t^* \quad (14)$$

Where $\text{diag}(E_f)$ is a diagonal matrix, whose elements are those of E_f ; $\text{diag}(E_t)$ is a diagonal matrix, whose elements are those of E_t ; I_f^* is the complex conjugate of I_f ; I_t^* is the complex conjugate of I_t .

Evidently, branch real power flow, branch real loss, branch reactive power flow and branch reactive loss are straightforward from the solved S_f, S_t .

$$\begin{aligned} P_{flow} &= \frac{1}{2} \text{Re}(S_f - S_t), & P_{loss} &= \text{Re}(S_f + S_t) \\ Q_{flow} &= \frac{1}{2} \text{Im}(S_f - S_t), & Q_{loss} &= \text{Im}(S_f + S_t) \end{aligned} \quad (15)$$

Along the same line, we build up “from” and “to” bus voltage vectors E_f^k, E_t^k based on E^k , and E_f^Q, E_t^Q based on E^Q , respectively. Corresponding branch current vectors $I_f^k, I_t^k, I_f^Q, I_t^Q$ can be obtained by substituting $E_f^k, E_t^k, E_f^Q, E_t^Q$ into (13) separately.

$$E_f = \sum_{k \in K} E_f^k + E_f^Q, \quad E_t = \sum_{k \in K} E_t^k + E_t^Q \quad (16)$$

Hence, we rewrite (15) based on the decomposed nodal voltage and branch current vectors.

$$S_f = \left(\sum_{k \in K} \text{diag}(E_f^k) + \text{diag}(E_f^Q) \right) \times \left(\sum_{k \in K} I_f^{*k} + I_f^{*Q} \right) \quad (17)$$

$$S_t = \left(\sum_{k \in K} \text{diag}(E_t^k) + \text{diag}(E_t^Q) \right) \times \left(\sum_{k \in K} I_t^{*k} + I_t^{*Q} \right)$$

Where $\text{diag}(E_f^k), \text{diag}(E_t^k), \text{diag}(E_f^Q), \text{diag}(E_t^Q)$ are respectively diagonal matrices, whose elements are those of $E_f^k, E_t^k, E_f^Q, E_t^Q$; $I_f^{*k}, I_t^{*k}, I_f^{*Q}, I_t^{*Q}$ are respectively complex conjugate of $I_f^k, I_t^k, I_f^Q, I_t^Q$.

From (17), specific contribution of individual transaction (say k) on the complex power injection S_f can be identified by

$$S_f^k = \left(\text{diag}(E_f^k) + \text{diag}(E_f^Q) \right) \times I_f^{*k} + f_{k,Q}^E \left(\text{diag}(E_f^k) \times I_f^{*Q} \right) + \sum_{m \in (K-k)} f_{k,m}^E \left(\text{diag}(E_f^k) \times I_f^{*m} \right) + \sum_{m \in (K-k)} f_{k,m}^I \left(\text{diag}(E_f^m) \times I_f^{*k} \right)$$

Where $f_{k,*}^E, f_{k,*}^I$ are sharing factors (scalar) for the cross term

between transactions k and another transaction named $*$. In particular, $0 \leq f_{k,*}^E \leq 1$, $0 \leq f_{k,*}^I \leq 1$, $f_{k,Q}^E = f_{k,Q}^I = 1$

From (18), it is seen that

1st term represents a self-induced component by transaction k , which relies on its own transaction as well as voltage support of the system reactive market, but independent of other energy transactions.

2nd term represents an interactive component between transaction k and reactive power exchange market.

3rd and 4th terms represent transaction k shared interactive components between itself and the remaining energy transactions.

Similarly, specific contribution of transaction k on the complex power injection S_t , denoted by S_t^k , can be derived.

In addition, transmission system usage by the central reactive power market is resolved by,

$$S_f^Q = \text{diag}(E_f^Q) \times I_f^{*Q}, \quad S_t^Q = \text{diag}(E_t^Q) \times I_t^{*Q} \quad (19)$$

It is clear that each transaction is solely responsible for its major term, the self-induced term. In addition, as a normal cost of consuming reactive power support, each energy transaction is responsible for the cross term between itself and the reactive power market. However, there is a flexibility to allocate cross terms among energy transactions, which can be designed into market game rules.

Evidently, as long as a consistent set of sharing factors (i.e., $\sum_{k \in K} f_{k,*}^E = \sum_{k \in K} f_{k,*}^I \equiv 1$) is adopted, it is satisfied that

$$S_f = \sum_{k \in K} S_f^k + S_f^Q, \quad S_t = \sum_{k \in K} S_t^k + S_t^Q \quad (20)$$

Real flow, real loss, reactive flow and reactive loss shares of individual transaction k or the single reactive market coordinator Q over each branch can be determined as follows,

$$P_{flow}^k = \frac{1}{2} \text{Re}(S_f^k - S_t^k), \quad P_{loss}^k = \text{Re}(S_f^k + S_t^k) \quad (21)$$

$$Q_{flow}^k = \frac{1}{2} \text{Im}(S_f^k - S_t^k), \quad Q_{loss}^k = \text{Im}(S_f^k + S_t^k)$$

$$P_{flow}^Q = \frac{1}{2} \text{Re}(S_f^Q - S_t^Q), \quad P_{loss}^Q = \text{Re}(S_f^Q + S_t^Q) \quad (22)$$

$$Q_{flow}^Q = \frac{1}{2} \text{Im}(S_f^Q - S_t^Q), \quad Q_{loss}^Q = \text{Im}(S_f^Q + S_t^Q)$$

The overall loss charge to each transaction is resolved by

$$P_{Tloss}^k = \sum_{ij \in L} P_{loss}^k, \quad Q_{Tloss}^k = \sum_{ij \in L} Q_{loss}^k, \quad \text{for each } k \in K \quad (23)$$

$$P_{Tloss}^Q = \sum_{ij \in L} P_{loss}^Q, \quad Q_{Tloss}^Q = \sum_{ij \in L} Q_{loss}^Q \quad (24)$$

Given that reactive power dispatch is to meet reactive loads and reactive losses from energy delivery, hence its induced real loss share should be further distributed among specific energy transactions. It is found that the transmission loss generated from reactive power flow is less than 10 percentage of the system real loss under the normal operating condition. For simplicity, we adopt a simple approach to reallocate them.

For energy transaction k , an extra transmission loss charge due to reactive power support is given by

$$P_{loss}^{(Q,k)} = \frac{\sum_{i \in N} Q_{D,i}^k + Q_{Tloss}^k}{\sum_{m \in K} \left(\sum_{i \in N} Q_{D,i}^m + Q_{Tloss}^m \right)} \times P_{Tloss}^Q, \quad \text{for each } k \in K \quad (25)$$

Then update P_{Tloss}^k obtained in (23) by the allocated $P_{loss}^{(Q,k)}$.

$$P_{Tloss}^k = P_{Tloss}^k + P_{loss}^{(Q,k)} \quad (26)$$

Up to now, all transmission losses are allocated to energy transactions, and are excluded from reactive power delivery settlement in response to Assumption-2.

Substituting P_{Tloss}^k derived from (26) into (5), updating real power output of each selected slack generator per energy transaction, we get a set of modified power flow equations (4). Repeat solving equation (4) for a new operating point (V_1, \mathbf{q}_1) , and re-allocate transmission losses for each transaction under the current operating point. This iteration process continues until transmission loss allocation remains unchanged. Normally, it takes 3~5 iterations of conventional AC power flow solution to converge. The overall flow chart is described below.

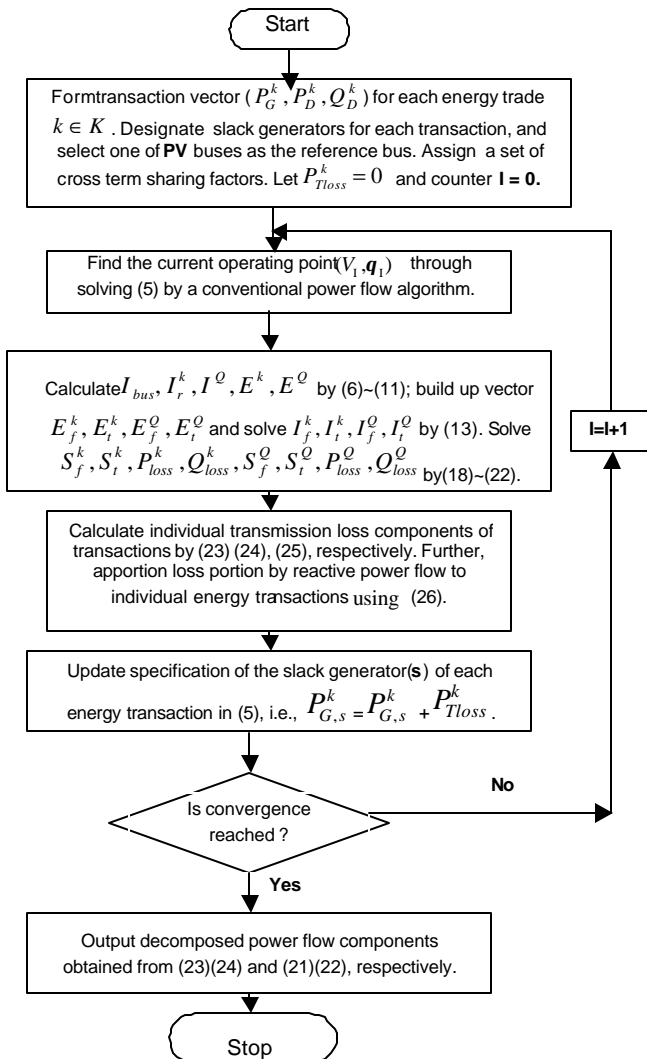
E. Market allocation rules

Evidently, the choice of cross term sharing factors has impacts on the transaction based power flow solution. To enhance power market stability, and to hedge firm or existing transactions against market risk due to inclusion of new

transactions, we propose two options for allocation of cross terms:

- Two simultaneous transactions (transactions with the same preference, say k and $*$) share their cross term (i.e., $f_{*,k}^E = f_{*,k}^I = f_{k,*}^E = f_{k,*}^I = 0.5$, while a later transaction (a lower preference, say k) takes care cross term by itself (i.e., $f_{k,*}^E = f_{k,*}^I = 1$, $f_{*,k}^E = f_{*,k}^I = 0$).
- A non-firm or unplanned transaction (say k) is responsible for the cross term itself (i.e., $f_{k,*}^E = f_{k,*}^I = 1$, $f_{*,k}^E = f_{*,k}^I = 0$), while the same type transactions share their cross term (i.e., $f_{*,k}^E = f_{*,k}^I = f_{k,*}^E = f_{k,*}^I = 0.5$).

F. Calculation flow chart



III. ILLUSTRATIVE EXAMPLES

The standard WSCC 9 bus power system is chosen to test the performance of the TBPf. The electrical component parameters are found in [9]. Without loss of the generality, a

central POOL market and two additional PTP type bilateral transactions are assumed. The network diagram is shown in Fig.1, associated with preferred interchange schedule data.

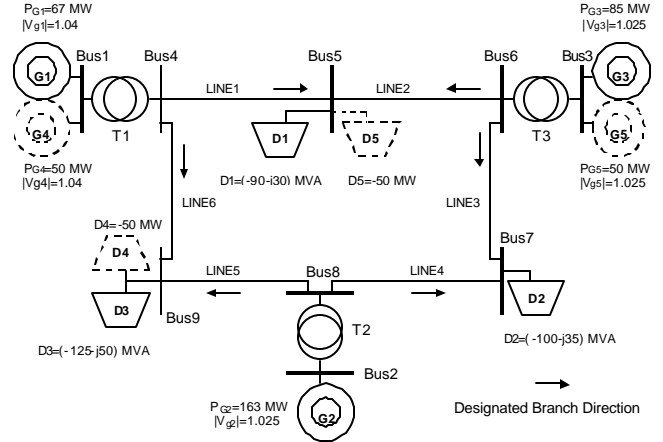


Fig.1. Diagram of The WSCC 9 Bus Test System & Preferred Exchange Schedules

The POOL operates three generators: G1,G2,G3 to supply three loads: D1,D2,D3 using the whole network; PTP-1 is scheduled to deliver 50 MW energy from G4 to D4 across LINE6 at individual 50 MW flowgate; PTP-2 is scheduled to deliver 50 MW energy from D5 to D5 across LINE2 at individual 50 MW flowgate. G 2 is designated as the slack generator of the POOL market, while two PTPs are needed to balance their own loads alone. In addition, the system operator (SO) is solely responsible for reactive power scheduling and settlement of the entire system. The available capacity of each transformer is 200 MVA; the total flowgate of each line is 100MW.

Next, we employ the TBPf for transmission utilization allocation and responsibility evaluation among various market players. In this example, the POOL market is treated as a base case, whereas PTP-1 and PTP-2 are processed as two simultaneous transactions. Hence, the cross term between the POOL and each PTP is solely attributed to the latter. Choosing Bus 2 as the reference bus (i.e., $q_2 = 0$), run the TBPf program to find an operating point. The decomposed line loss components are displayed in Table 1.

Table 1. Line Loss Decomposition Results (Unit: MW)

BRANCH	POOL	PTP-1	PTP-2	QSC	Σ
T1	0	0	0	0	0
LINE1	0.1080	0.0595	0.1404	0.1116	0.4195
*LINE2	1.3999	-0.3491	2.2711	0.0804	3.4024
T2	0	0	0	0	0
LINE3	0.0437	0.0429	0.0990	0.0339	0.2195
LINE4	0.4902	-0.0704	-0.1541	0.0162	0.2819
T3	0	0	0	0	0
**LINE5	2.3706	0.3840	0.8251	0.1721	3.7517
*LINE6	0.0748	0.3779	-0.1155	0.2665	0.6037
Σ	4.4872	0.4448	3.0660	0.6807	8.6787

Note: T1,T2,T3 are three transformer branches. PTP-2 reserves half transmission capacity (50MW) of LINE2; PTP-1 reserves half transmission capacity (50MW) of LINE6. LINE5 is congested after two PTPs are imposed. Qsc is the reactive power market.

From Table 1, it is noted that

- The delivery of three energy transactions produces a dominant loss share of 7.998 MW (i.e., 92.16% of the system loss), while the reactive power flow of the system takes up the remaining loss portion of 0.6807 MW (i.e., 7.84% of the system loss).
- Comparing the two bilateral transactions, we note that PTP-1 generates a small loss quantity of 0.4448 MW, while PTP-2 generates a large loss quantity of 3.066 MW. A DC power flow analysis can be used to verify this result. DC flow results are shown in Table 2.

Table 2: DC Power Flow Results (Unit: MW)

Branch	POOL	PTP-1	PTP-2	The Total
T1	67	50	0	117
LINE1	28.9674	6.2427	12.4853	47.6954
*LINE2	61.0326	-6.2427	37.5147	92.3046
T2	85	0	50	135
LINE3	23.9674	6.2427	12.4853	42.6954
LINE4	76.0326	-6.2427	-12.4853	57.3046
T3	163	0	0	163
**LINE5	86.9674	6.2427	12.4853	105.6954
*LINE6	38.0326	43.7573	-12.4853	69.3046

From Table 1 and 2, it is found that most power of PTP-2 flows over a few heavy or congested lines like line 2 and line 5. By contrast, PTP-1 generates a negative flow in line 2 whose line loss rises to 3.4024 MW, and generates a smaller positive flow in the congested line than PTP-2. As a result, PTP-1 is awarded by a negative loss share of -0.3491 MW in line 2, and is charged with a small positive loss share of 0.3840 MW. On the other hand PTP-2 is charged with two large positive loss shares: 2.2711 MW and 0.8251 MW in line 2 and line 5, respectively. This validates that loss decompositions obtained from the TBPF reflect the actual system usage.

In addition, directly from the solution of the TBPF, interaction losses between different energy transactions are derived as follows.

Table 3: Interactive loss terms (unit: MW)

	POOL	PTP-1	PTP-2
POOL	4.487	0.3815	2.5129
PTP-1	0.3815	0.1508	-0.1751
PTP-2	2.5129	-0.1751	0.6406

The values of Table 3 should be read in this way: a non-diagonal term represents the interaction between two energy transactions, while a diagonal term is a summation of the major term of a single energy transaction and the interaction between itself and the reactive power market.

As shown in Table 3, the interaction loss between two PTP type transactions is negative, while other interaction losses between POOL and any PTP are positive. This also matches with DC power flow results in Table 3.

Finally, taking extra 0.6807 MW loss caused by reactive support into account using equation (26) above, we obtain the transmission loss and reactive loss allocations as follows,

Table 4: Transmission Loss Allocation Results (unit: MW)

Trade	POOL	PTP-1	PDP-2	The System
Loss Shares	5.0698	0.4759	3.1329	8.6787

Table 5: Reactive Loss Allocation Results (unit: MVAR)

Trade	POOL	PTP-1	PTP-2	Qsc
Loss Shares	45.8506	8.6046	18.4737	-129.6634

Note: Qsc takes care almost all of the total line charging – 138.0766 MVAR.

Meanwhile, active power flow decomposition results are obtained in Table 6.

Table 6: Active Power Flow Decompositions (MW)

Branch	POOL	PTP-1	PTP-2	Qsc	Line Flows
T1	65.66	46.31	2.38	3.12	117.48
LINE1	28.05	4.68	12.64	2.33	47.70
*LINE2	61.46	-6.02	38.36	0.42	94.22
T2	84.18	-0.03	53.57	0.42	138.13
LINE3	22.00	6.14	14.03	-0.06	42.11
LINE4	76.87	-6.43	-13.40	1.10	58.14
T3	165.25	-0.13	0.66	2.30	168.07
**LINE5	86.95	6.14	13.74	1.10	107.91
*LINE6	37.52	41.41	-10.27	0.60	69.27

To compare Table 2 and Table 6, it is seen that the absolute value difference between DC flows and TBPF active power flows is only 3.69 MW at maximum (over Branch T1), in comparison to the system loss of 8.6787 MW. It reflects that DC power flow analysis has “reasonable” accuracy to estimate active power flows for these cases. It is interesting that reactive power delivery Qsc induces small active power flow components in the network.

To investigate the accuracy of the TBPF approach, we now increase an extra 10 MW exchange to PTP-1 and PTP 2 separately. New loss allocations from the TBPF’s solution are shown in Table 7.

Table 7: Incremental Transmission Loss Allocation Results

		PTP1+10 MW	PTP2+10 MW
Loss (MW)	POOL	5.0928	5.1013
	PTP-1	0.6298	0.4574
	PTP-2	3.1199	3.9506
Variation	POOL	+ 0.4537 %	+ 0.6213 %
	PTP-1	+ 32.3387 %	- 3.8874 %
	PTP-2	- 0.4150 %	+ 26.1004%

Note: the variation (%) is based on loss charges in Table 4.

It is noted that incremental loss is automatically allocated to the increased transaction, with a maximum -3.8874% impact.

It verifies that the loss charge signal of the TBPF is compatible with that of the incremental evaluation scheme. However, the incremental method relies on a base case power flow solution, and does not deal with simultaneous transactions effectively. The TBPF is self-reliant, and handles both sequential and simultaneous transactions effectively.

To show that the TBPF provides more accurate curtailment signal for congestion management than the GAPP method, we calculate power transfer distribution factors (PTDFs) for the only congested line in Table 8.

Table 8: The PTDFs in terms of LINE 5

	POOL	PTP-1	PTP-2
GAPP based PTDFs	0.2761	0.1249	0.2497
TBPF based PTDFs	0.2760	0.1227	0.2745

Because parallel flow components of two PTPs over the congested LINE 5 increase the loading of the line with no reserved transmission right, the responsibility to reduce the congestion is only limited to two bilateral transactions, and may not re-dispatch the POOL’s generation. According to the solved PTDFs, we determine curtailment amounts of two PTP type transactions so that the line congestion can be

eliminated after the curtailment. A curtailment of transaction k to reduce congestion in line $(i - j)$ is estimated by

$$\Delta P^k = K_A \times \frac{P_{flow,i-j} - P_{Limit,i-j}}{\sum PTDF_{i-j}^m} \times \frac{PTDF_{i-j}^k}{\sum PTDF_{i-j}^m}, \quad K_A \geq 1.0$$

Substitute PTDFs, the solved real flow over line 5, and the assigned flowgate (=100 MW) into the above equation to find the needed transaction curtailments. Then modify transactions and re-run the TBPF. The results are tabulated as follows,

Table 9: Transaction Curtailment & Reduced Line Flow ($K_A=1.8$)

	Transaction Curtailments		Flow in Line 5 After curtailment
	Δ PTP-1	Δ PTP-2	
PTDFs (GAPP)	-9.145	-18.257	101.917 MW
PTDFs (TBPF)	-11.07	-24.773	99.883 MW

Unit: MW

It demonstrates that the TBPF based curtailment scheme is more effective than the GAPP's in congestion management.

When two PTP transactions and the POOL are performed simultaneously, the TBPF will find a new operating point, where loss charge to the POOL has a significant increase due to sharing of interactive components. By means of allocation of interactive flow and loss components, the TBPF enables the ISO to hedge firm or existing transactions against market risk due to addition of non-firm or new transactions.

IV. CONCLUSION

To perform the competitive power market efficiently, the system operator need to assess and manage transaction-oriented power flows in the unbundled transmission grid. At the present time, NERC, along with the entire industry is strive to develop efficient methods to estimate diverse power flow components on a particular facility, such as: (i) power flow due to dispatch of pool-type energy market; (ii) power flow due to point-to-point (PTP) type transmission service or bilateral transactions; (iii) parallel power flow resulting from the dispatch of neighboring pool-type energy markets; (iv) parallel power flow resulting from the PTP-type transmission service or bilateral transactions [10]. Numerous test results based on WSCC9, IEEE30, IEEE57 RTS systems demonstrate the proposed TBPF has sufficient potentials to assess various interchange schedules at ex ante phase or real-time balancing stage. In general, the TBPF has several advantages as follows,

1. The solved operating point is based on energy transactions.
2. Accurate allocation of use-of-transmission is part of the TBPF solution.
3. The TBPF provides more accurate active power flow decompositions than a DC power flow results.
4. The transmission loss responsibility is self-evident for each transaction. Loss allocation by the TBPF provides consumers with a useful economic signal, i.e., high loss charged to an energy transaction indicates that its shared transmission paths are heavily loaded.
5. High computation efficiency. It is quite suitable for both on-line implementation and off-line analysis.

6. It provides potential means for voltage stability assessment and pricing of reactive power on individual transaction basis.

Finally, it should be pointed out that though we assume that only a reactive power market exists in the system in this paper, the general case of multiple reactive power markets can be easily extended by dividing the system-wide reactive power market into several smaller local ones, where cross terms among different reactive power markets will be shared.

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VI. BIOGRAPHY

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